

Observing Rotation-powered Pulsars and Magnetars in the X-ray and Gamma-Ray Sky

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Cargese, 13-14 April 2006



Observing Rotation-powered Pulsars and Magnetars in the X-ray and Gamma-Ray Sky

PART 2

- Status and Recent Observations of SGRs and AXPs
 - Focus on major progress over last 4 years for AXPs:
AXP are magnetars!
- - Discovery of luminous pulsed hard X-ray emission
from AXPs
- Magnetar Model (Predictions)

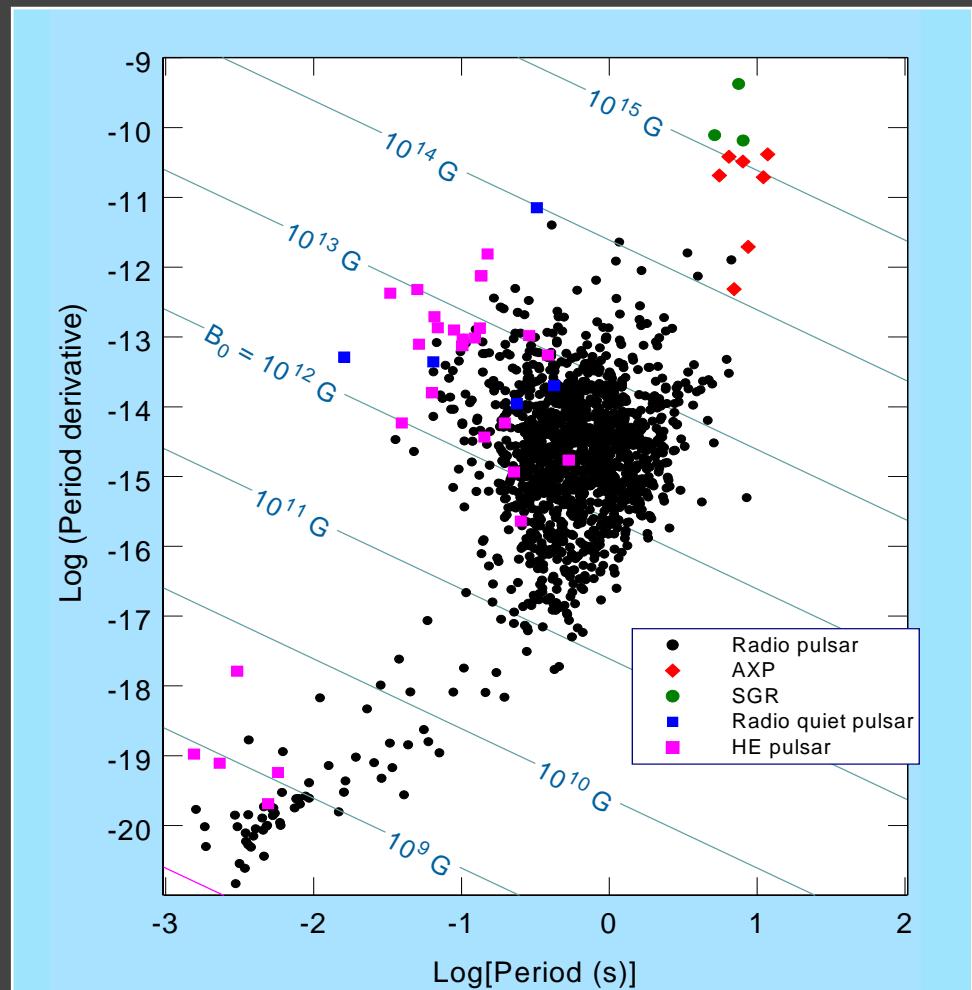
Rotation-Powered Pulsars and Magnetars:

P–P diagram with $B_0 = B_s$

- ~1500 radio pulsars
- ~30 X-ray pulsars
- 10 γ-ray pulsars
- 7 AXPs
- 5 SGRs

Extreme B fields:

- AXPs & SGRs $10^{14} - 10^{15}$ G
- Millisecond pulsars $10^8 - 10^{10}$ G
(old “recycled” pulsars,
spun-up by accretion torques
in a binary system)



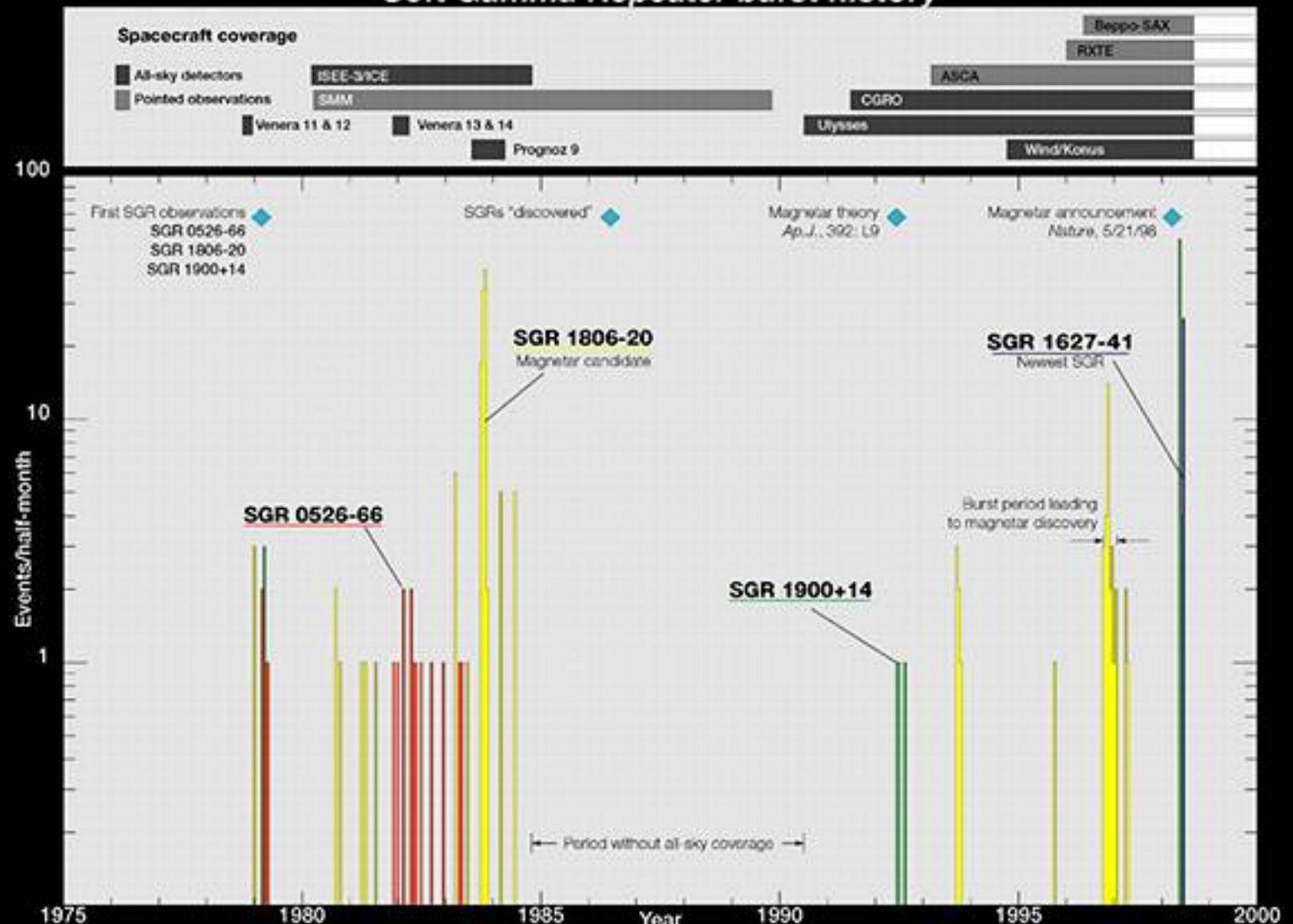
Magnetar properties

	SNR	P (s)	dP/dt (10^{-11} s/s)	B (10^{14} G)	kT(keV) / Γ	L (10^{33} erg/s) (0.2-10keV)
4U 0142+61		8.7	0.2	1.3	0.46 / 3.4	72
1E 2259+586	CTB 109	7.0	0.05	0.6	0.41 / 3.8	17 - 59
1E 1048-5937		6.4	2-3	3.9	0.63 / 2.9	5.3 - 25
1E 1841-045	Kes 73	11.8	4.0	7.1	0.44 / 2.0	110
XTE 1810-197		5.5	1.8	2.9	0.67 / 3.7	10 - 260
RXS J1708-4009		11	2.0	4.7	0.44 / 2.4	190
CXO J0110-72	in SMC	8.0	1.8	3.9	0.38 / 2.0	200
Westerlund 1		10.6	<20	-	0.61	3
AX J1845-0258	G29.6+0.1	7.0	-	-	/ 4.6	5 - 120
SGR 1900+14	G42.8+0.6?	5.2	6.1-20	5.7	0.43 / 2.0	200 - 350
SGR 1806-20	G10.0-0.3?	7.5	8.3-47	7.8	0.6 / 1.4	320 - 540
SGR 0526-66	N49 in LMC	8.0	6.6	7.4	0.53 / 3.1	260
SGR 1627-41	G337.0-0.1?	6.4 ?	-	-	/ 2.9	4 - 100
SGR 1801-23		-	-	-	-	-

History Soft Gamma-Ray Repeaters

- First SGR detected with the “**March-5-1979** event”, SGR 0526-66: Satellite triangulation pointed to LMC
- 1985-1986 : Bursts appear to come from the plane of the Milky Way
- 1992: Magnetar theory (Duncan & Thompson)
- 1996: 7.8-s period found for SGR 1806-20 in RXTE data (Kouveliotou et al.)
- 1998: Nature paper : **SGRs are magnetars**

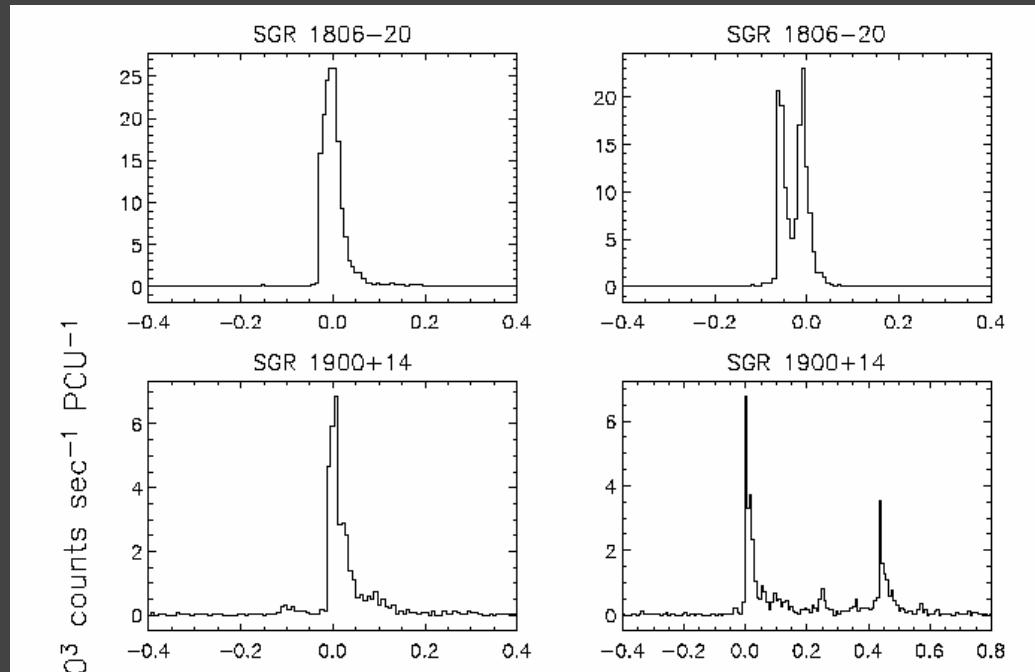
Soft Gamma Repeater burst history



SGR bursts

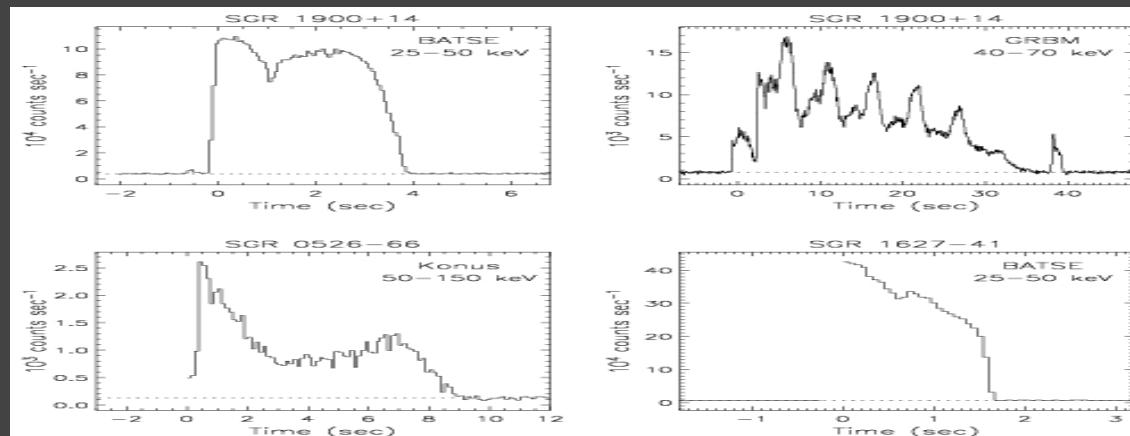
Short bursts

- the most common
- they last ~ 0.1 s
- peak $\sim 10^{41}$ ergs/s
- soft γ -rays thermal spectra



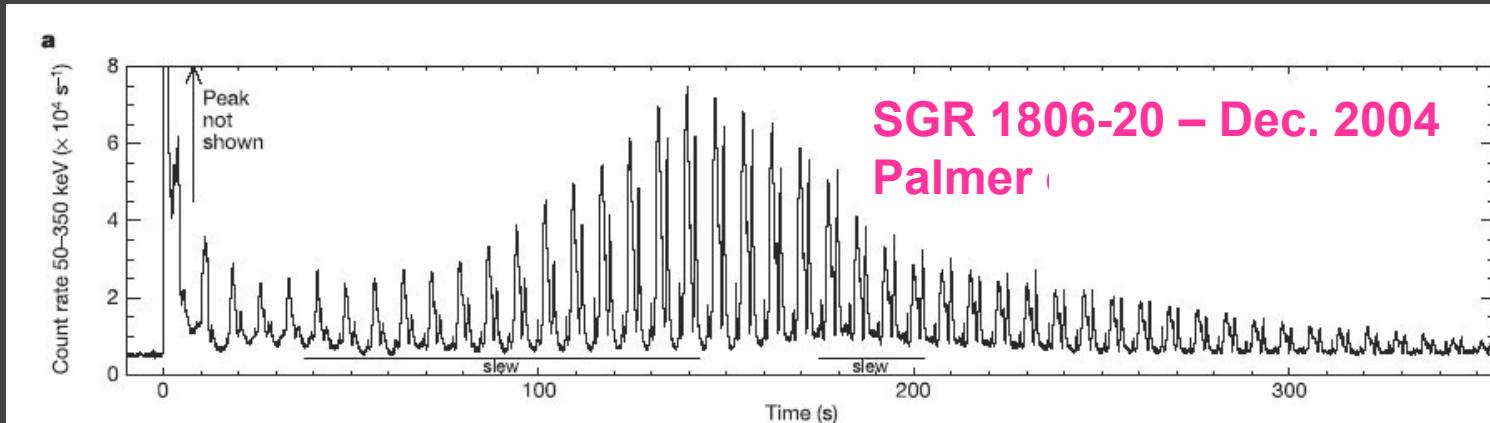
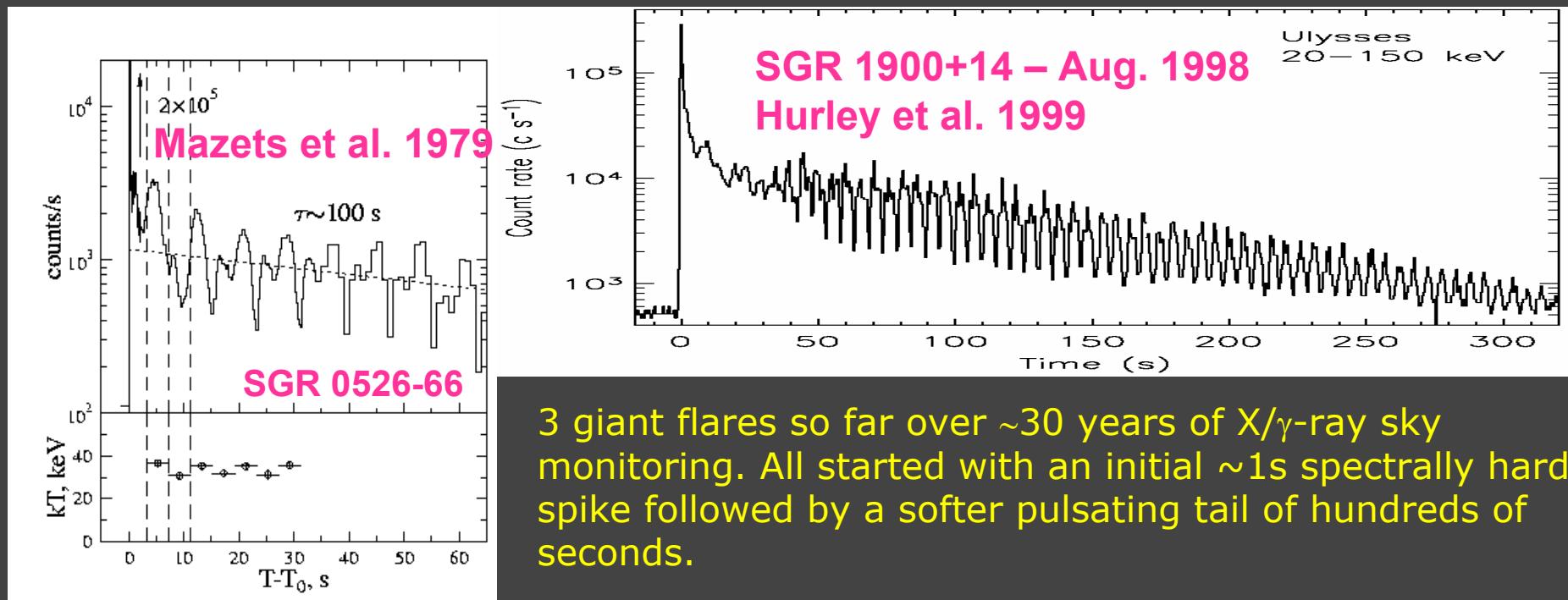
Intermediate bursts

- they last 1-40 s
- peak $\sim 10^{41}$ - 10^{43} ergs/s
- abrupt on-set
- usually soft γ -rays thermal spectra

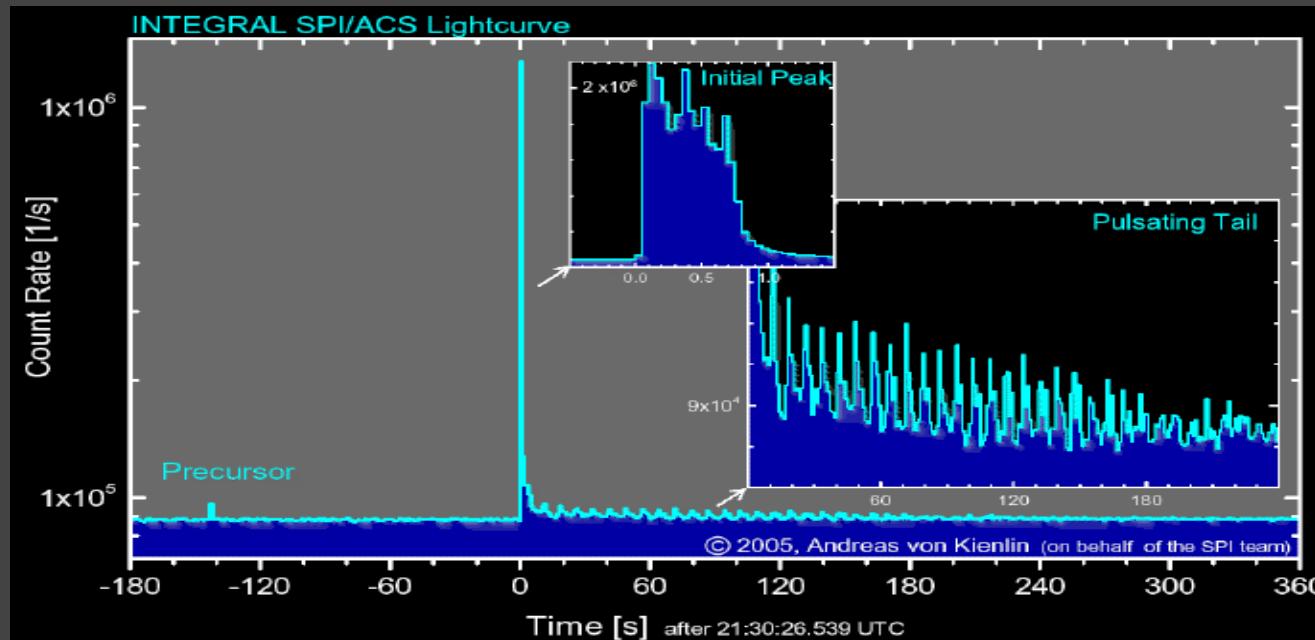


SGR giant flares

$$L_F \sim 10^{45}\text{--}10^{47} \text{ erg}$$

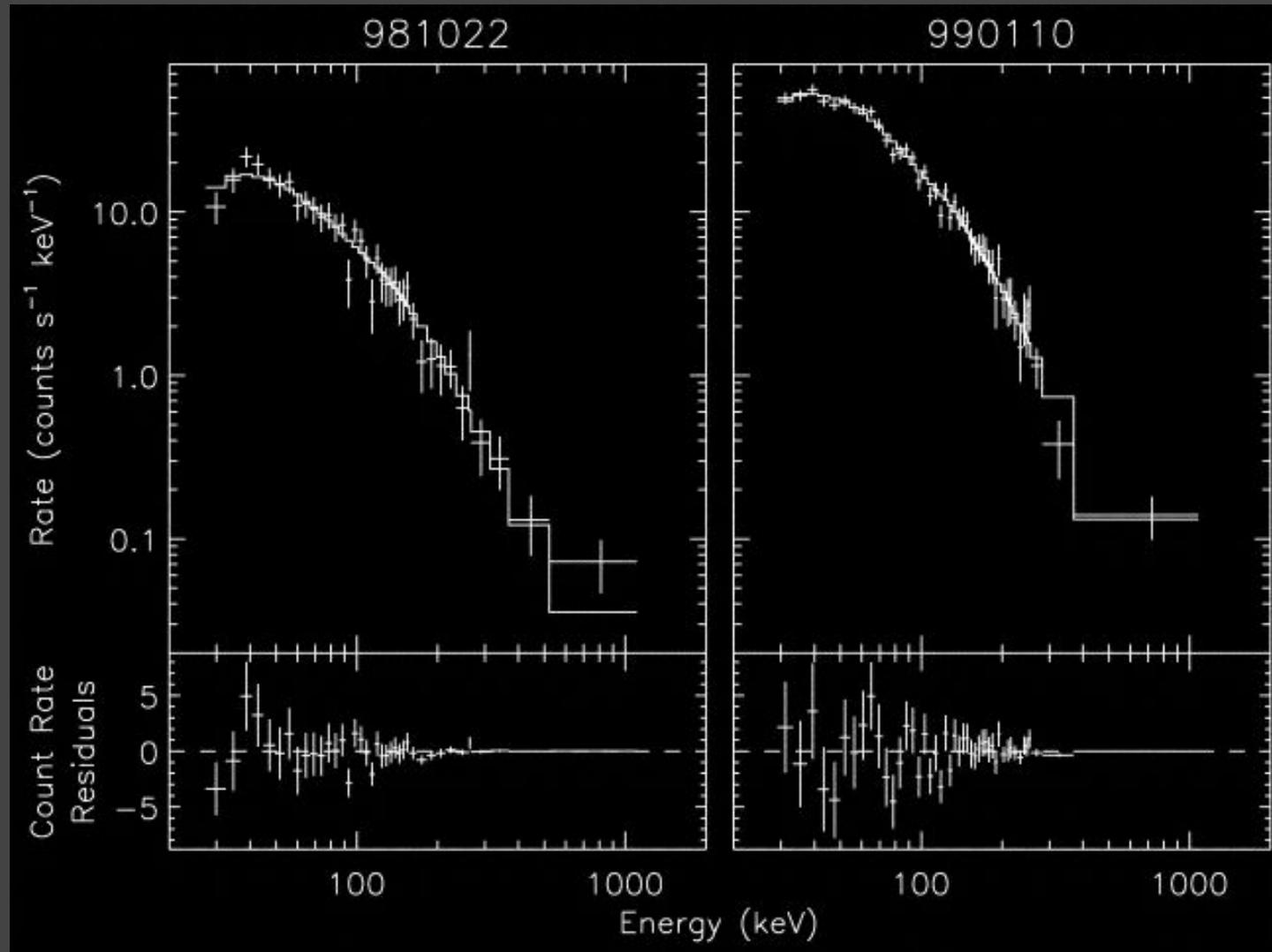


SGR 1806-20 catastrophic event



- ~ 0.2 s + 50 cycles pulsating tail ($P \approx 7.56$ s)
- An ISOTROPIC! released energy of $2 \times 10^{46} d_{15}^2$ erg in the spike and $5 \times 10^{43} d_{15}^2$ erg in the tail
- The isotropic energy in the initial spike was 100 times larger than in the other two flares, while the energy in the tail was comparable.
- The spike's spectrum was roughly modelled by a thermal emission of $kT \sim 0.5$ MeV with a 45 keV - 10 MeV flux, integrated over the first 0.16s, of $5\text{ erg cm}^{-2}\text{s}^{-1}$
- Radio expanding nebula produced by the flare with a luminosity 500 times larger than in the case of SGR 1900+14.

SGR Spectra for steady and burst emission

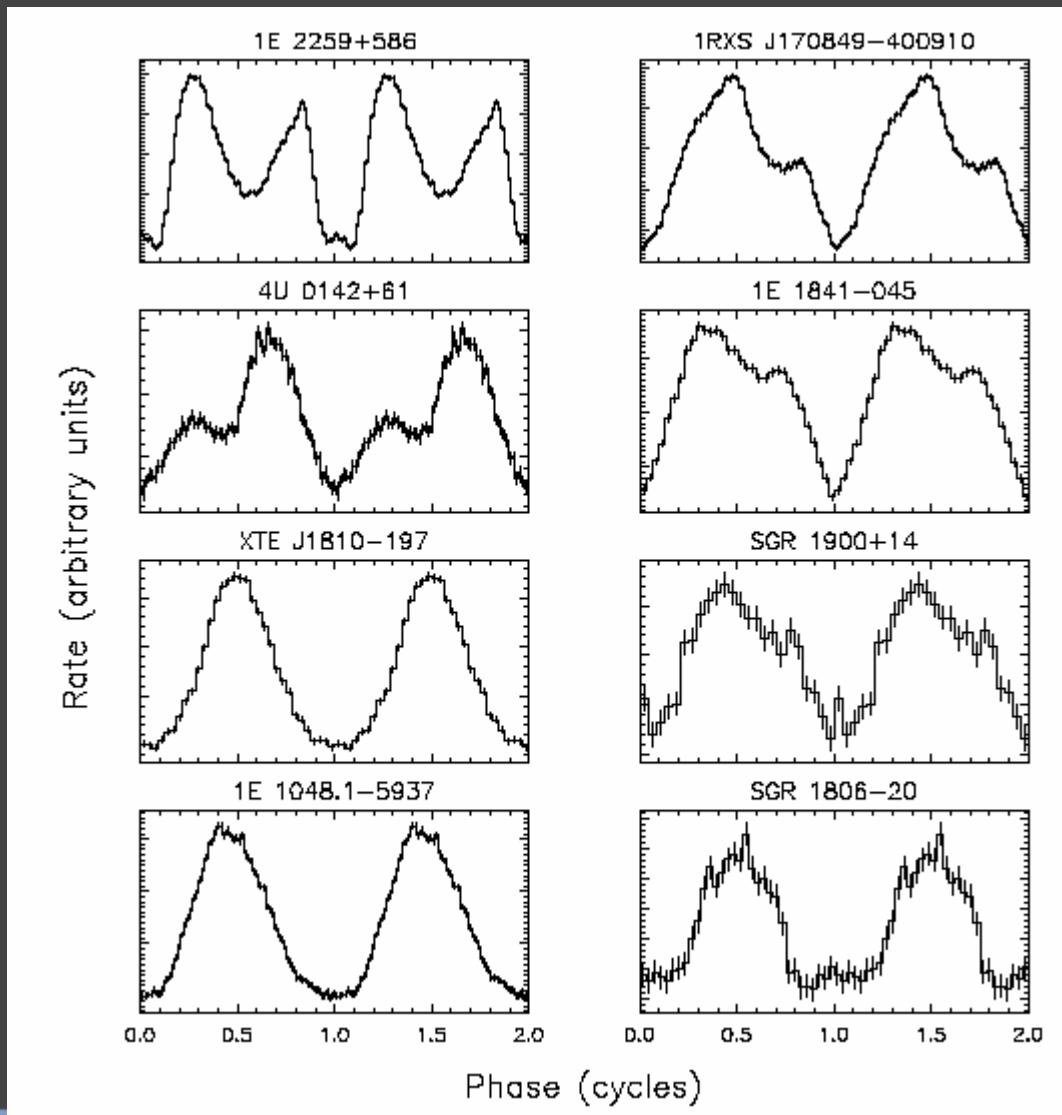


SRON Soft spectra with e.g. Bremstrahlung spectrum \sim 30 keV

Quiescent emission pulse profiles of AXPs and SGRs E<10keV

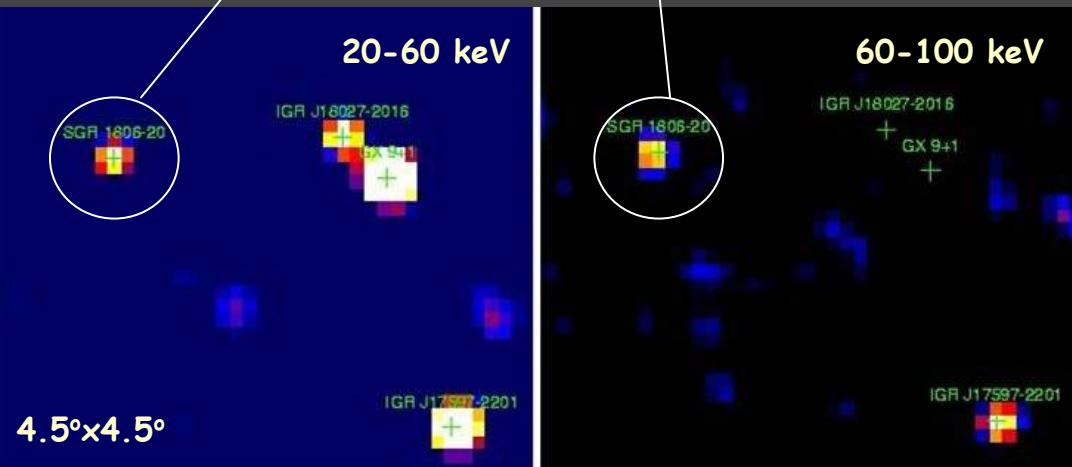
Woods & Thompson 2004

$$L_Q \sim 10^{35} \text{ erg s}^{-1} >> L_{SD} \sim 10^{33} \text{ erg s}^{-1}$$

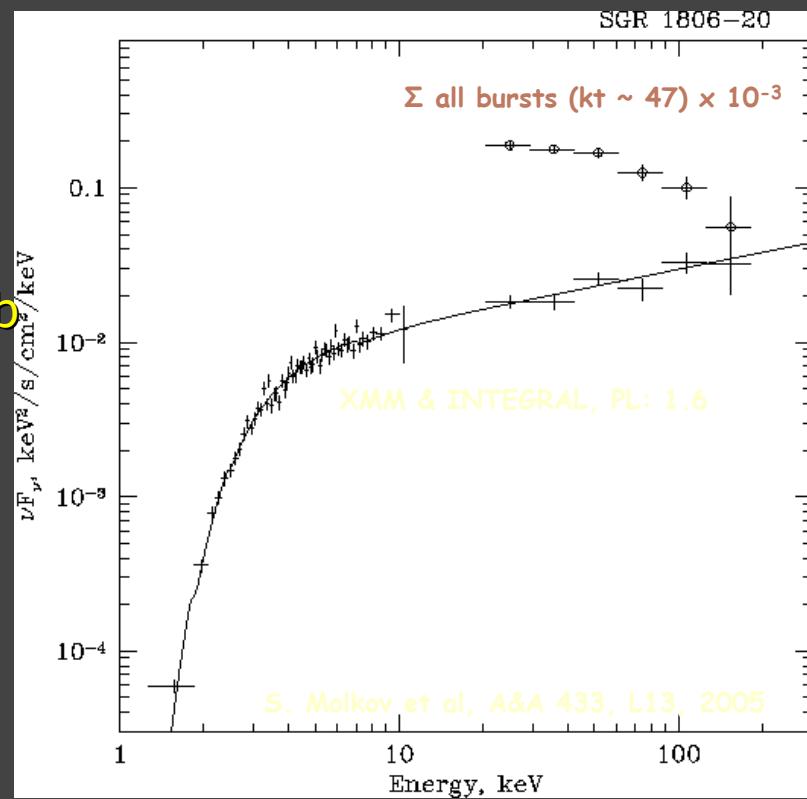


SGR 1806-20 persistent emission S. Mereghetti et al., A&A 433, L9, 2005

- Hard X-ray imaging capabilities crucial for crowded region !
- INTEGRAL detection of persistent emission > 20 keV, 10^{36} erg/s or 3 mCrab
- Non-thermal emission in magnetosphere



S. Mereghetti et al., A&A 433, L9, 2005



Recently INTEGRAL also **SGR 1900+14** (Götz et al. 2006)

Anomalous X-ray pulsars (status around 2003-2004) Bright Uhuru sources: Are AXPs Magnetars ?

- No rotation powered pulsar
 - No X-ray pulsar in LMXB/HMXB
(no accretion-powered pulsar)
- $L_X >> L_{sd}$
steady spin-down; no apparent optical counterpart; no periodic Doppler delay in X-ray timing

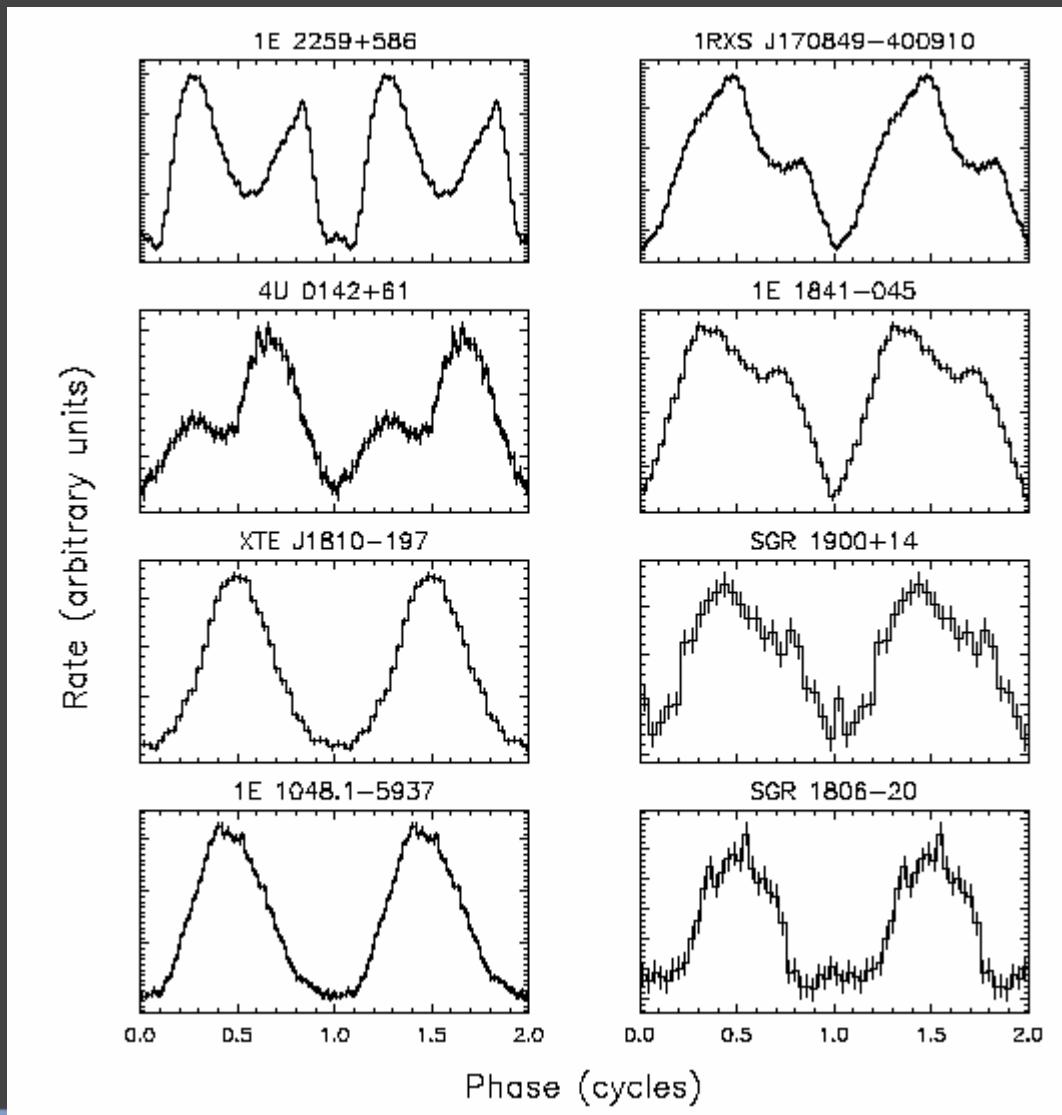
Characteristics:

- ◊ Pulse periods: 5 -12 s
- ◊ "Steady" spin-down like rotation powered pulsars (glitches observed also)
- ◊ X-ray luminosities: 10^{34-36} erg/s (steady, but outbursts also detected; transient AXPs)
- ◊ (very) soft X-ray (0.5-10 keV) spectra: BB (0.35 – 0.6 keV) + PL (2 – 4)
- ◊ Similar to Soft Gamma-Ray Repeaters → Magnetars (glitches; (out)bursts)
- ◊ Young population concentrated along galactic plane

Quiescent emission pulse profiles of AXPs and SGRs E<10keV

Woods & Thompson 2004

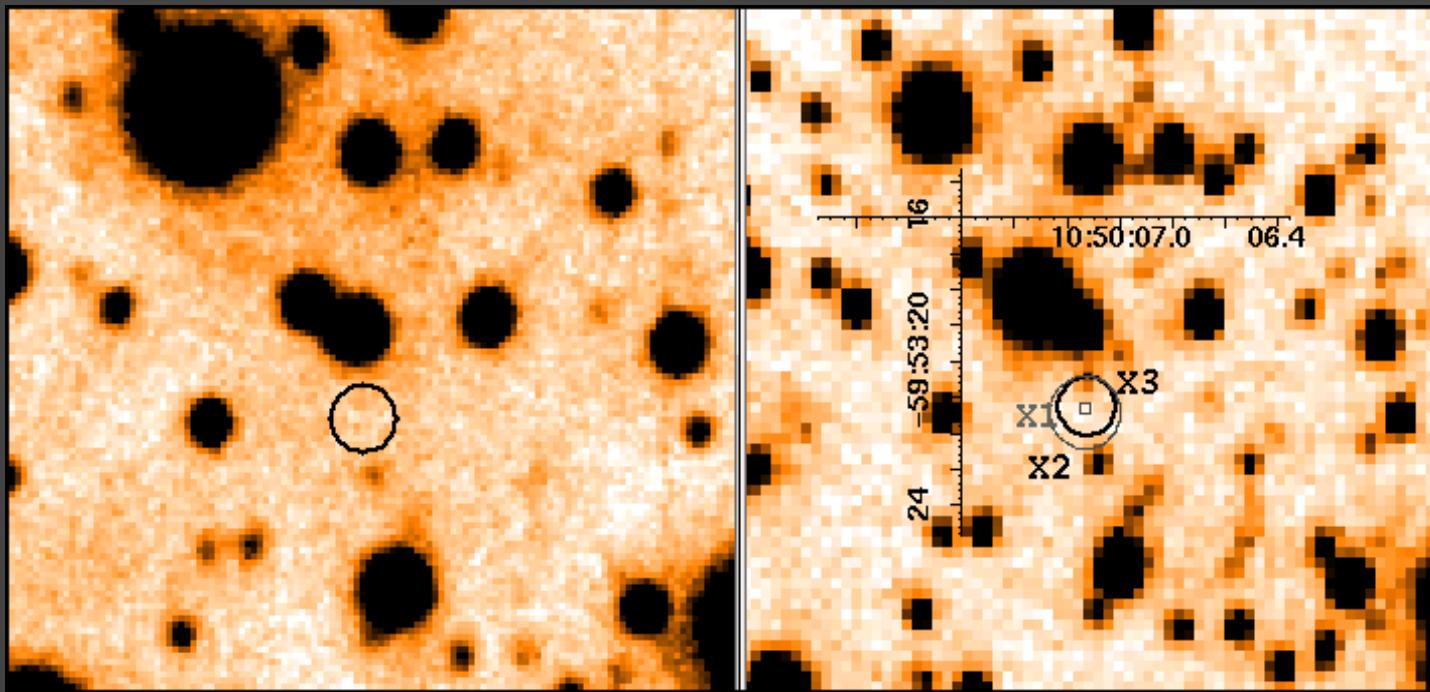
$$L_Q \sim 10^{35} \text{ erg s}^{-1} >> L_{SD} \sim 10^{33} \text{ erg s}^{-1}$$



AXPs: Searches for companions

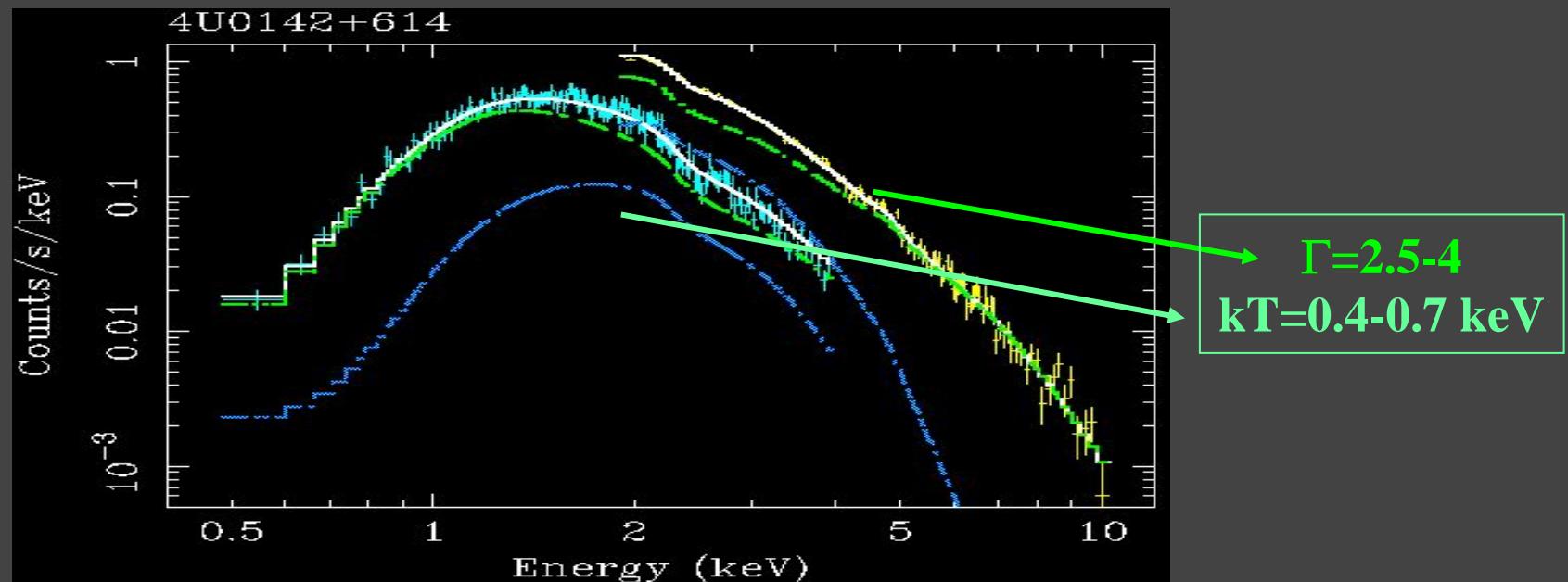
WDs or very very low-mass companions?

Constraints on the mass of a possible companion achieved from optical/IR observations and from the lack of any Doppler delay in the X-ray pulsations.



1E1048-59
 $I > 23.5$ $K_s > 20.1$
ESO NTT -
Chandra err rad = 0.8"

Soft spectra of AXPs, example: 4U 0142+614



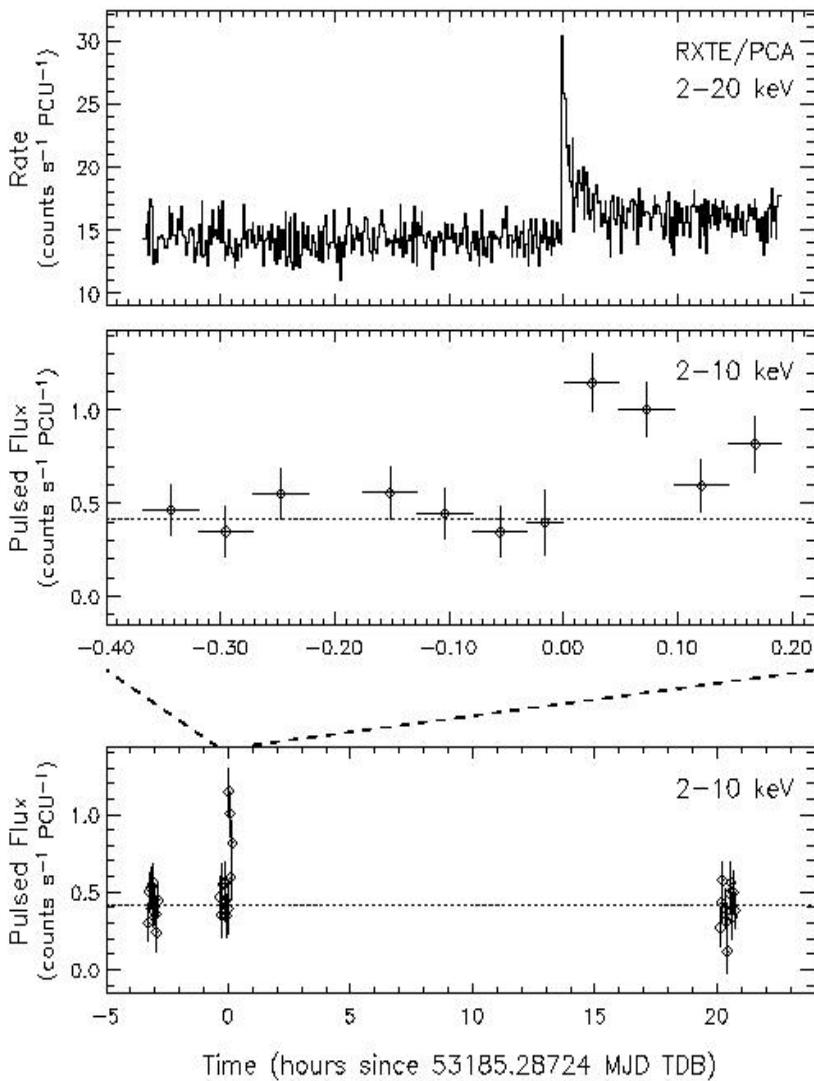
Also, variable X-ray fluxes below 10 keV (Rea et al. 2004, 2005)

Bursts from AXPs!

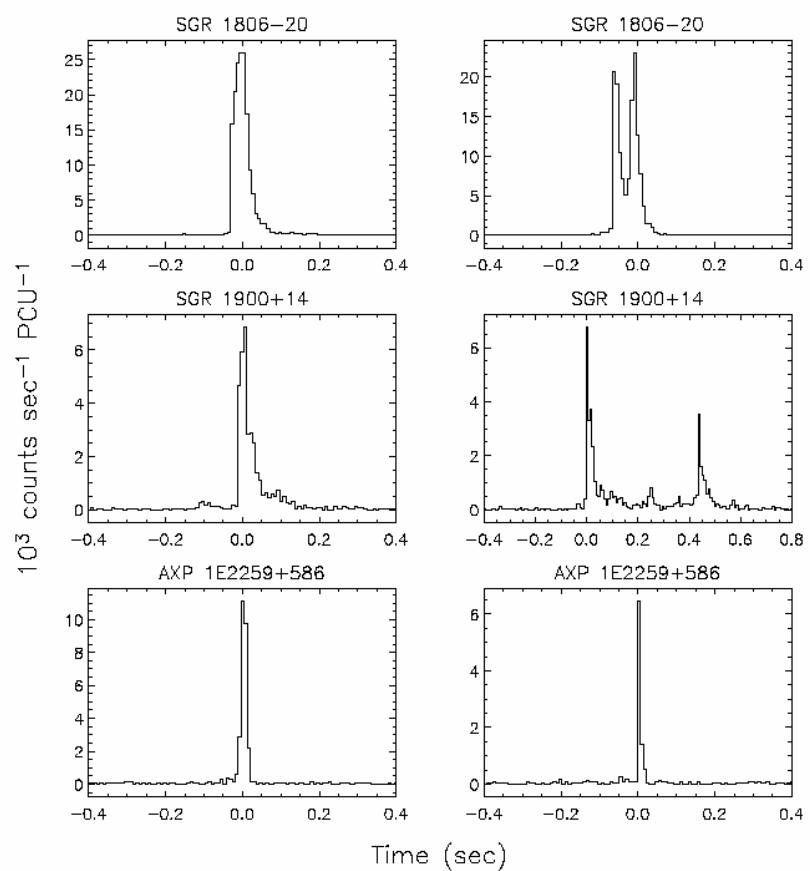
Note: SGR 0526-66 (Kulkarni et al. 2003)

June 2004 Burst from 1E 1048-5937

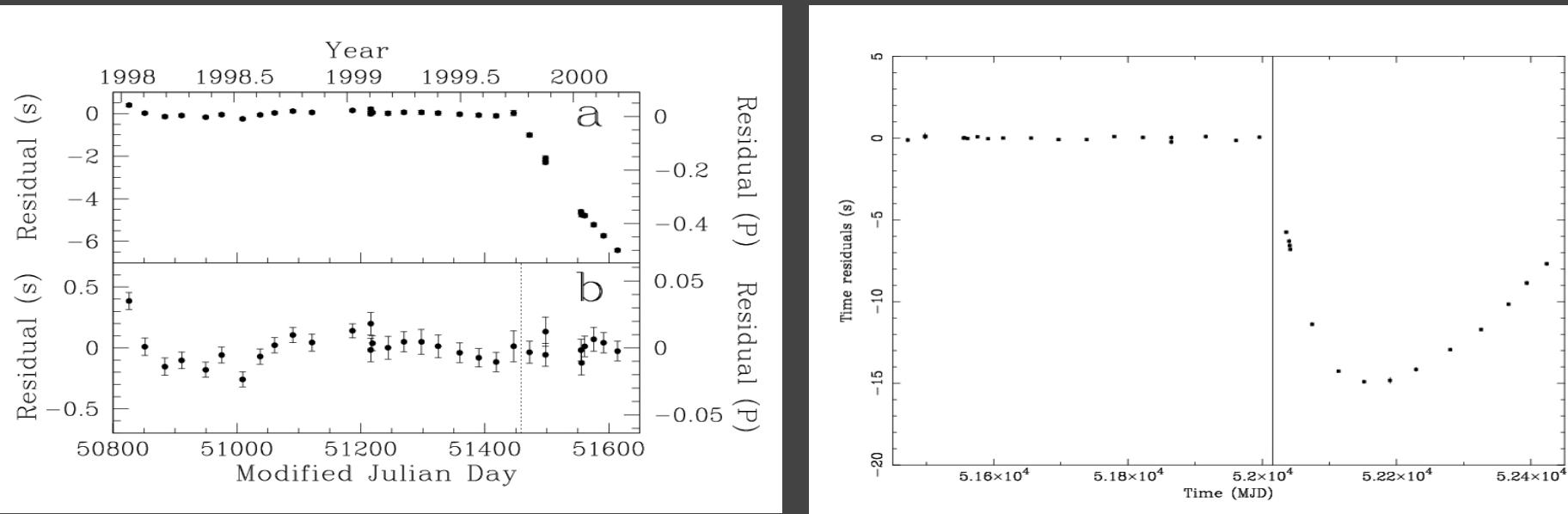
Gavriil, Kaspi & Woods 2005



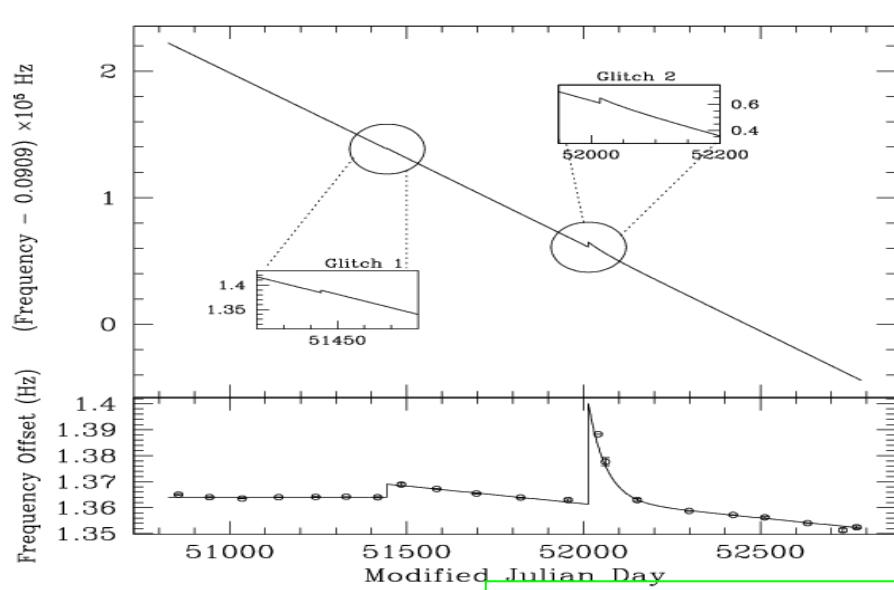
Bursts from AXPs predicted by magnetar model of Thompson & Duncan (1996)



The glitch phenomenon for AXP 1E 2259+586



$\Delta\omega/\omega = 6.5 \times 10^{-7}$
 $\Delta\dot{\omega}/\dot{\omega} = 1.7 \times 10^{-2}$
Vela-like glitch

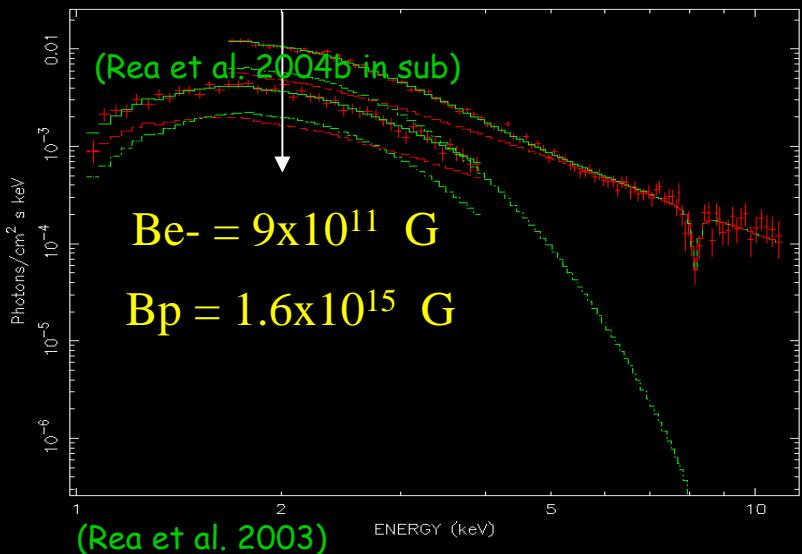
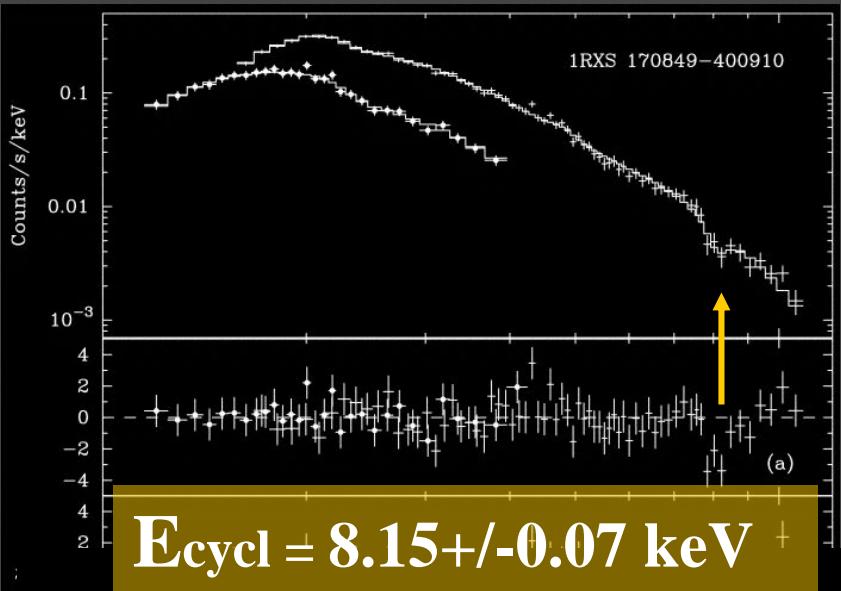


$\Delta\omega/\omega = 3.9 \times 10^{-6}$
 $\Delta\dot{\omega}/\dot{\omega} = 9 \times 10^{-3}$
Crab-like glitch

(Kaspi et al. 2001; Dall'Osso et al. 2003; Kaspi & Gavriil 2003)

Cyclotron lines (However..., see next slide)

RXS J1708-4009



SGR 1806-20

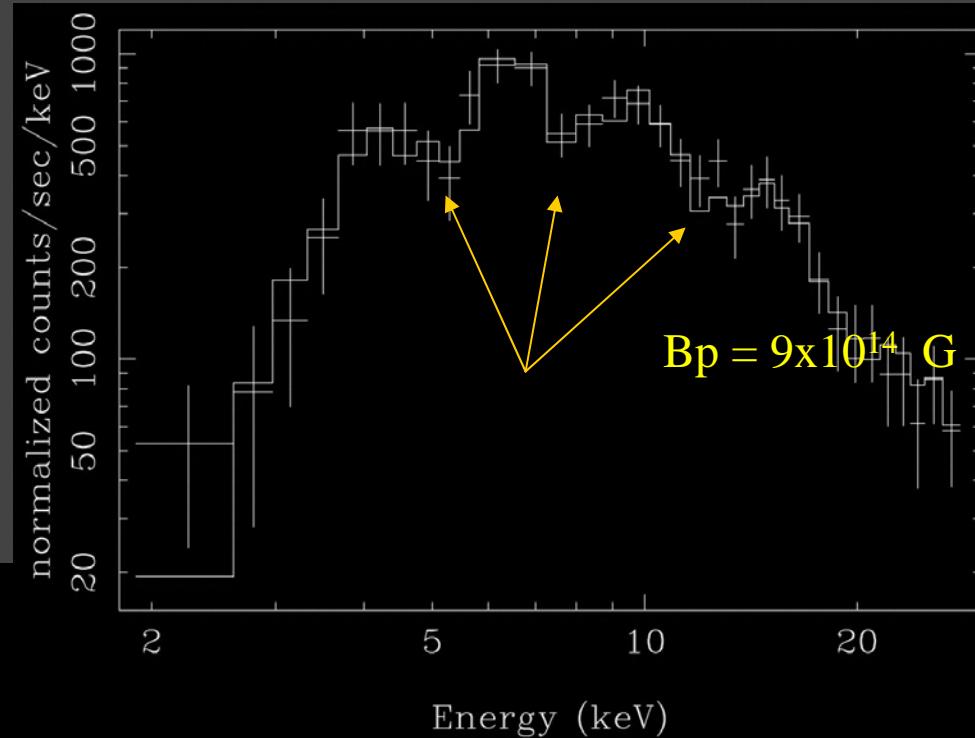


TABLE 2
BEST-FIT PARAMETERS FOR THE LINE FEATURES

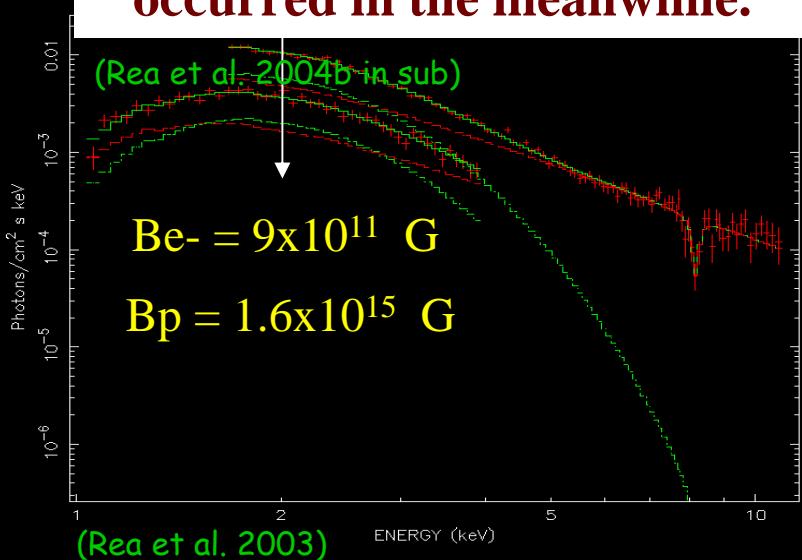
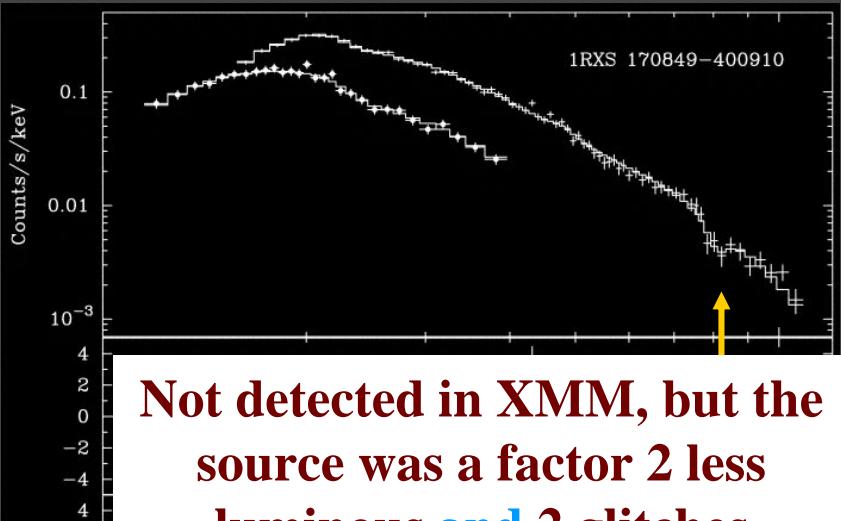
Line Feature	Energy (keV)	Width (keV)	Depth
1	5.0 ± 0.2	0.24 ± 0.1	1.9 ± 0.6
2	7.5 ± 0.3	0.45 ± 0.2	1.2 ± 0.4
3	11.2 ± 0.4	1.2 ± 0.5	0.9 ± 0.3
4	17.5 ± 0.5	1.1 ± 0.7	1.0 ± 0.4

NOTE.—The cyclotron absorption model is described in Mihara et al. 1990.

(Ibrahim et al. 2003)

Cyclotron lines

RXS J1708-4009



SGR 1806-20

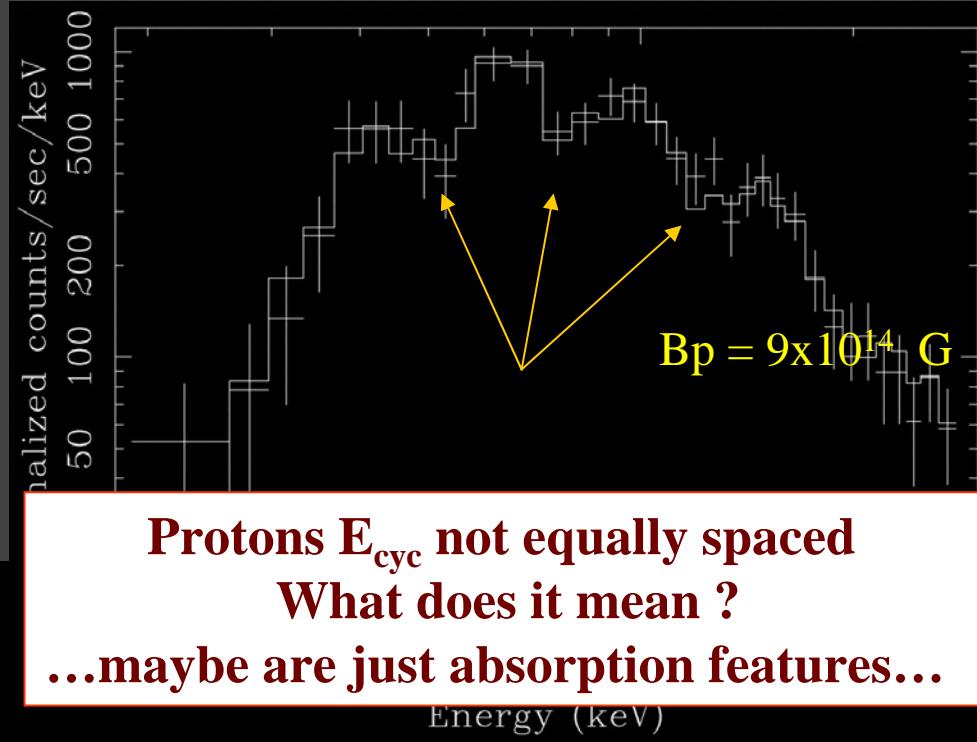


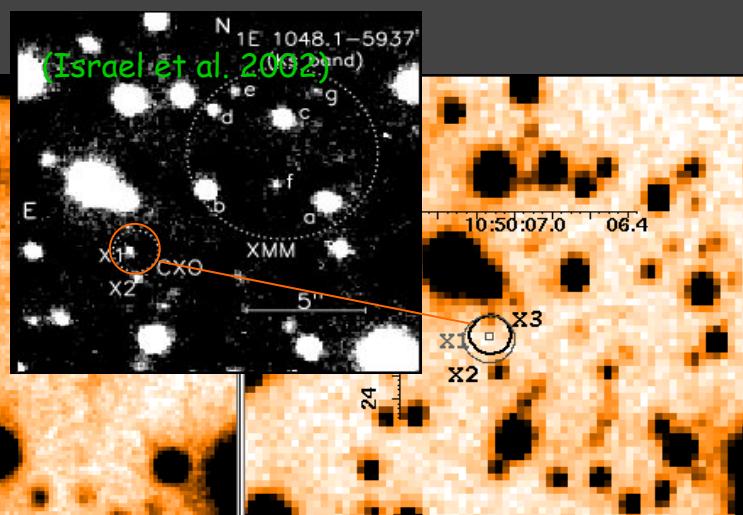
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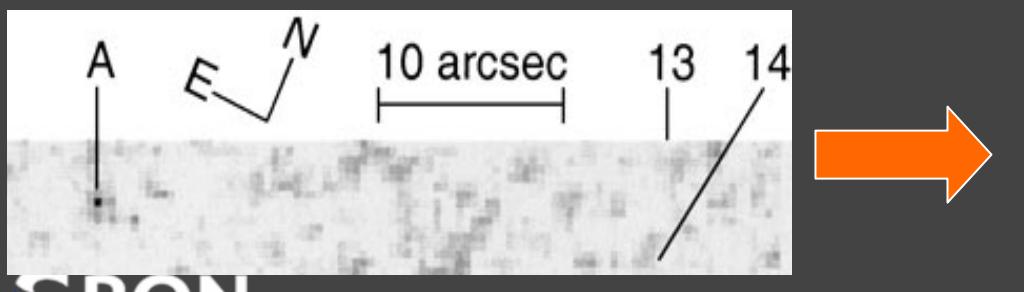
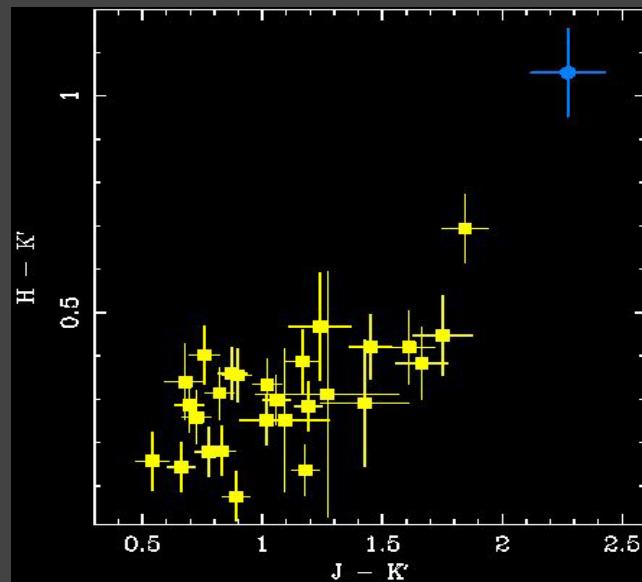
NOTE.—The cyclotron absorption model is described in Mihara et al. 1990.
(Ibrahim et al. 2003)

Multiwavelength studies of AXPs

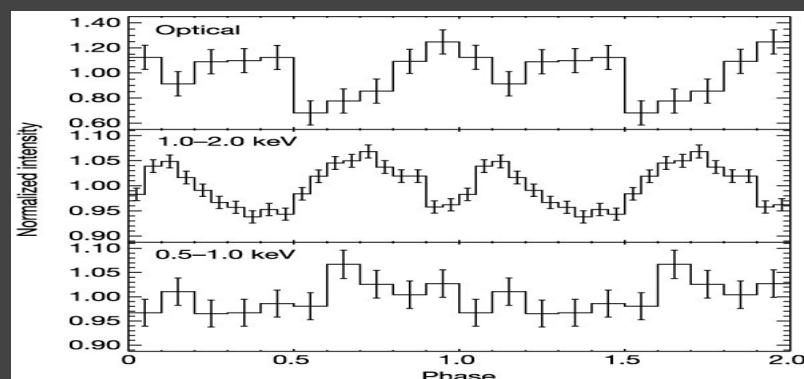
In the last few years IR counterparts were detected for almost the whole AXP sample, in three of them was also revealed an IR variability (roughly magnitudes are: $K_s = 20-22$, $H = 21-23$, $J \geq 21$ but all with strange colours...). All the AXPs except one, 4U 0142+06, do not show (so far) optical emission. (see also Durant et al. 2003; Israel et al. 2003; Rea et al. 2004)



IR variability in 1E 1048-59. X1 is not detected 50 days before implying $\Delta K_s > 1.3$ (factor of 3 in flux)



Optical pulsation from 4U 0142+61: $R=25$ mag and $PF=26\% > PF$ in X-rays



(Kern & Martin 2002)

AXPs soft magnetars?



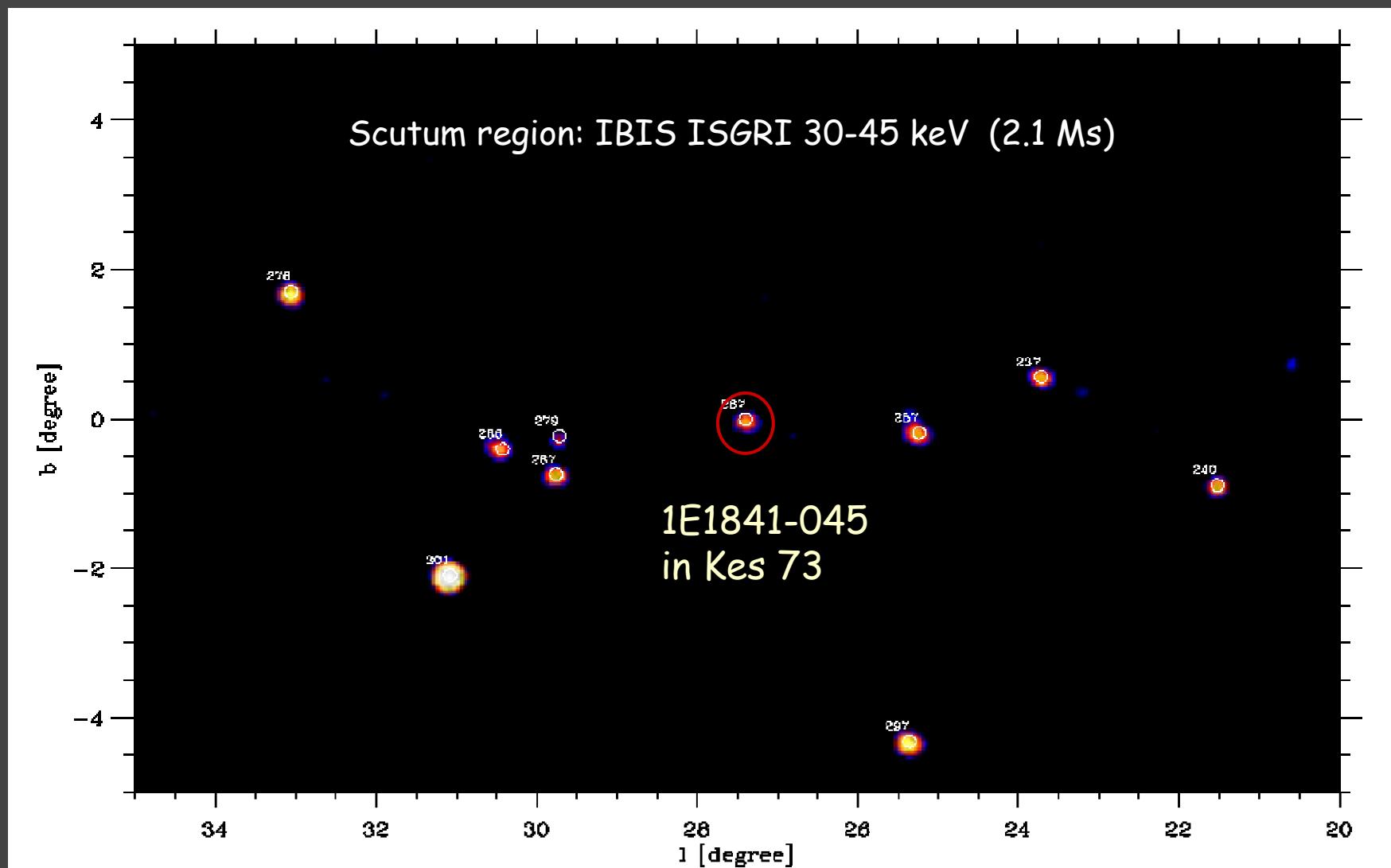
**Discovery of luminous pulsed
hard X-ray emission from AXPs**

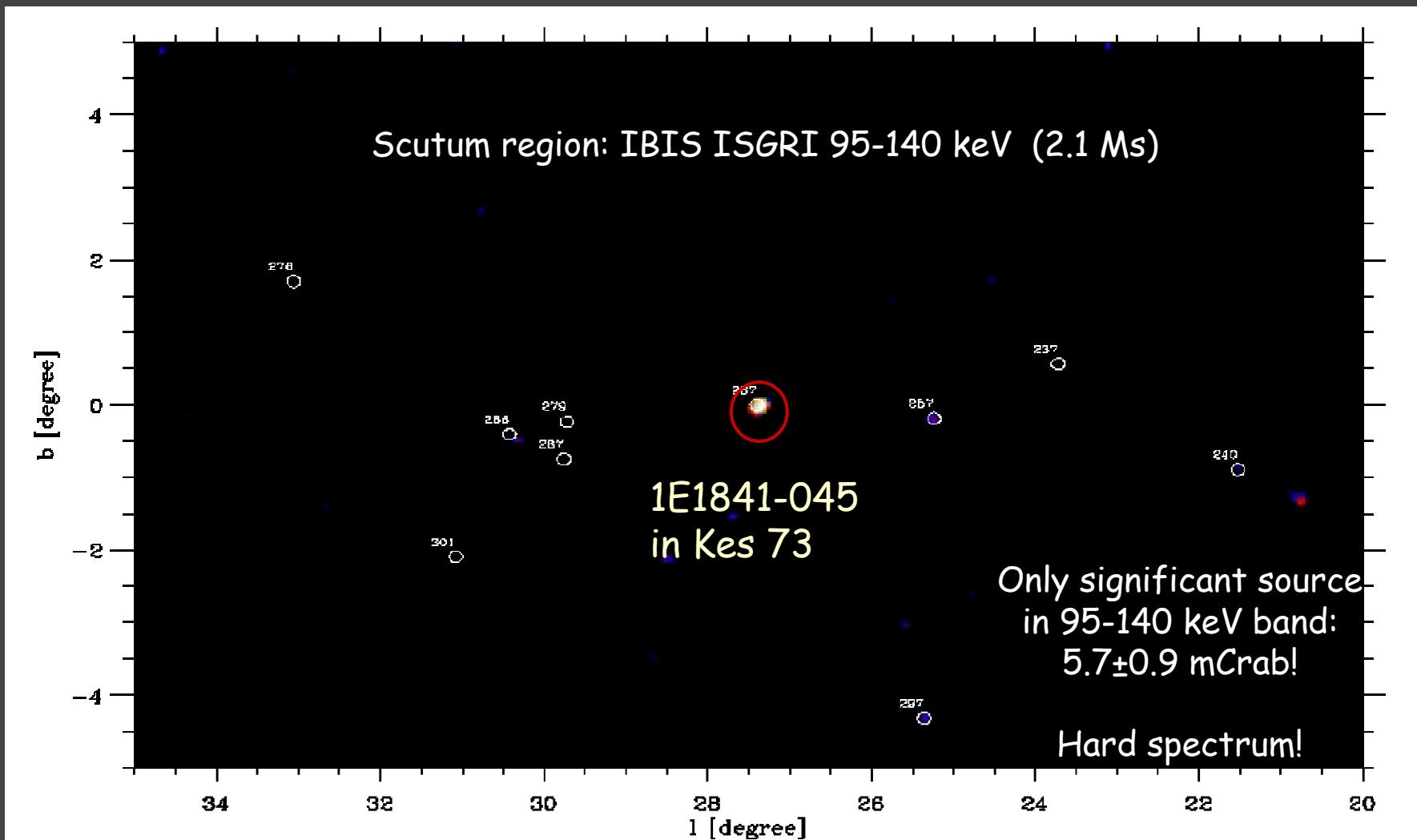
Kuiper, Hermsen & Mendez 2004

Kuiper, Hermsen, den Hartog & Collmar
astro-ph/603467 2006

den Hartog et al. astroph 2006

AXP research at soft γ -rays triggered by the detection of a point source
in an IBIS ISGRI 18-60 keV map at SNR Kes 73 (Molkov et al. 2004)



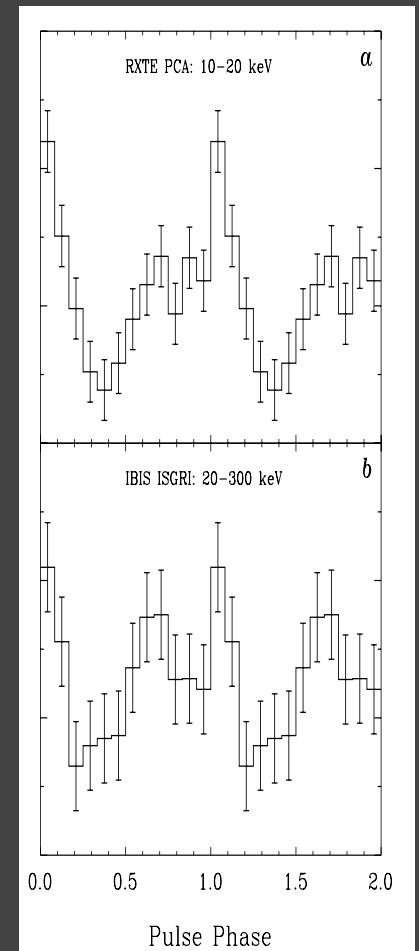
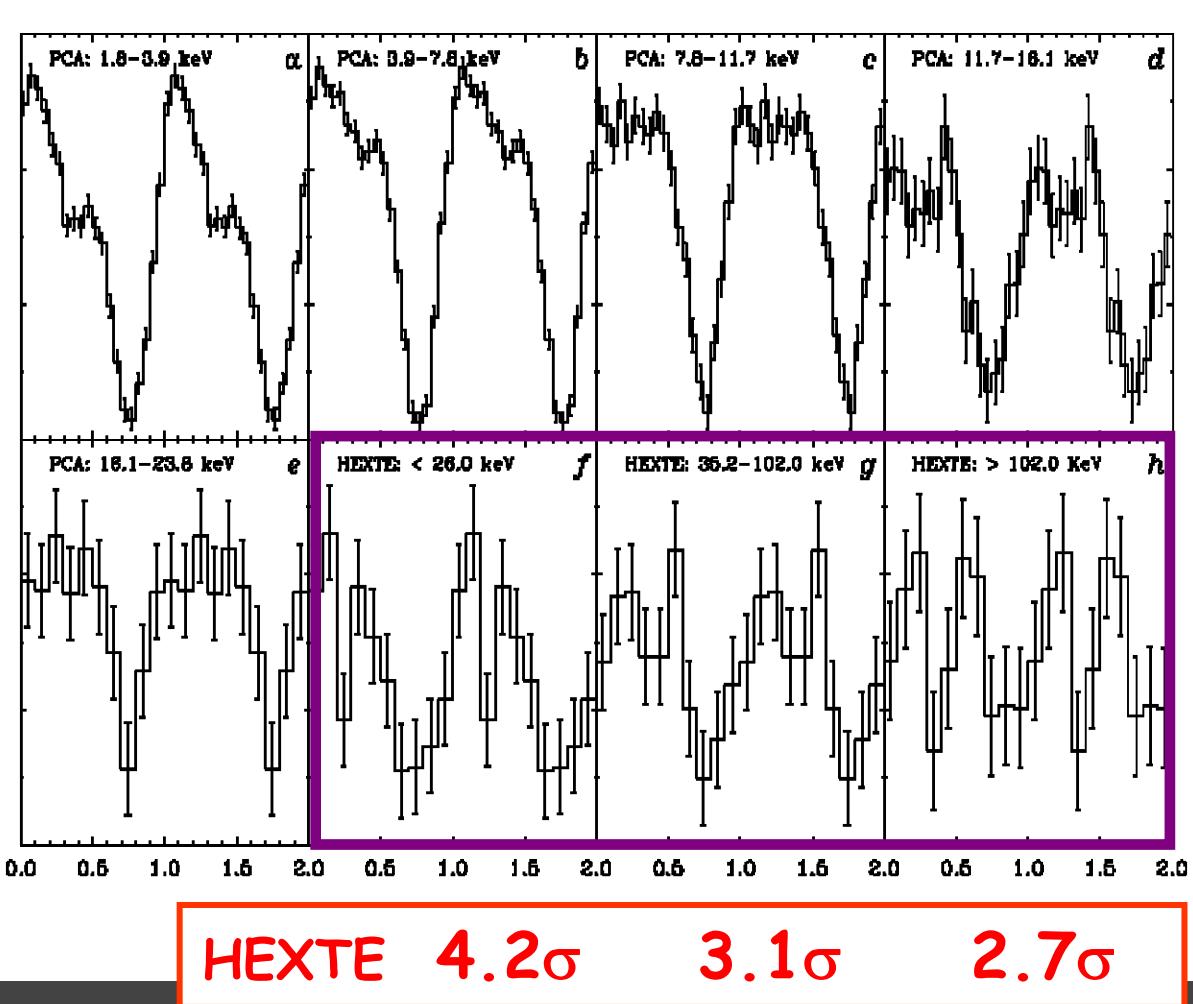


Archival RXTE PCA/HEXTE data

Kuiper, Hermsen & Mendez 2004, ApJ 613, 1173

RXTE/INTEGRAL Contemporaneous

Kuiper, Hermsen, den Hartog, Collmar 2006, ApJ



High Energy Spectra SNR Kes 73 and AXP 1E 1841-045

1 Kes 73 +
1E 1841-045
XMM-Newton

2 Total
1E 1841-045
Chandra
(Morii et al. 2003)

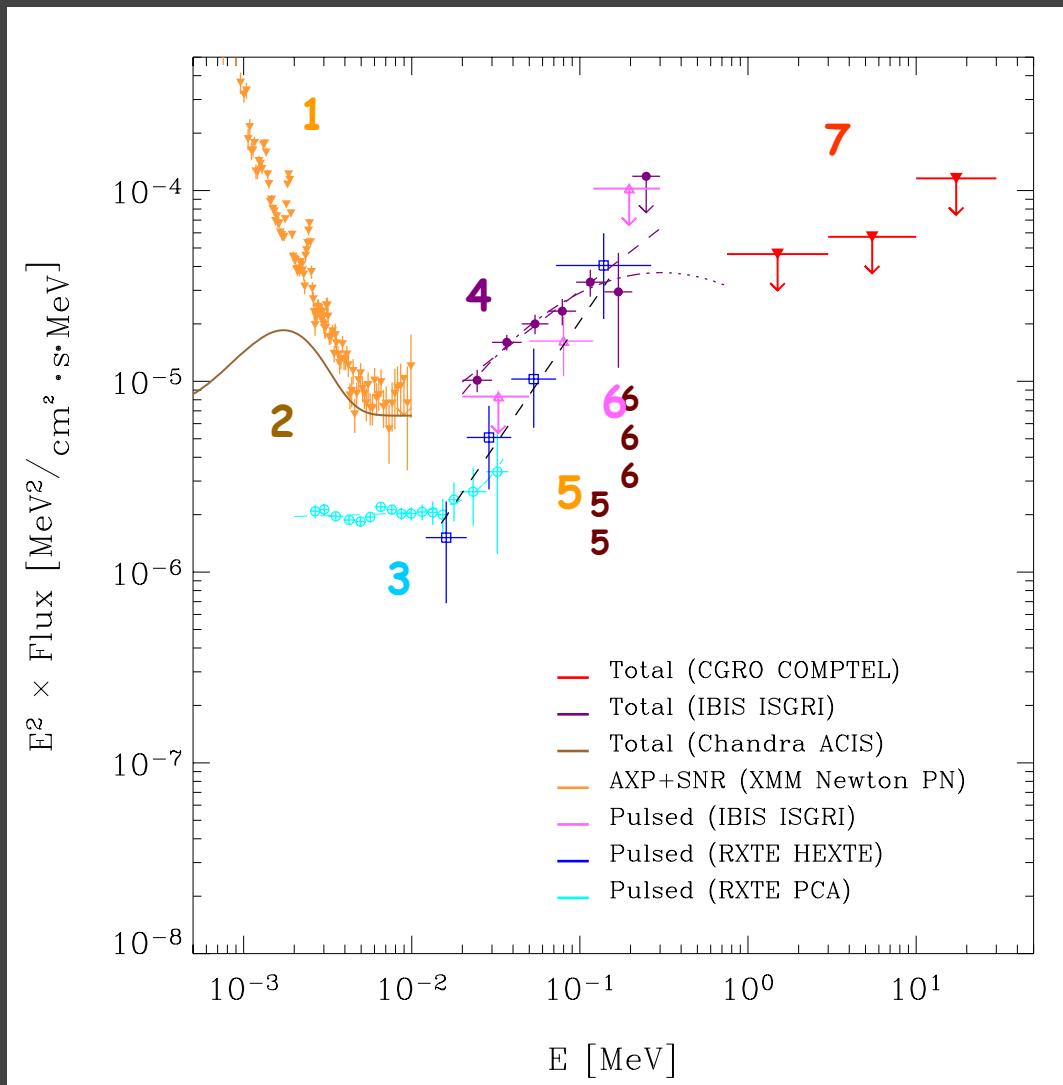
3 Pulsed
1E 1841-045
RXTE/PCA

4 Kes 73? +
1E 1841-045
IBIS ISGRI
 $\Gamma = 1.32 \pm 0.11$

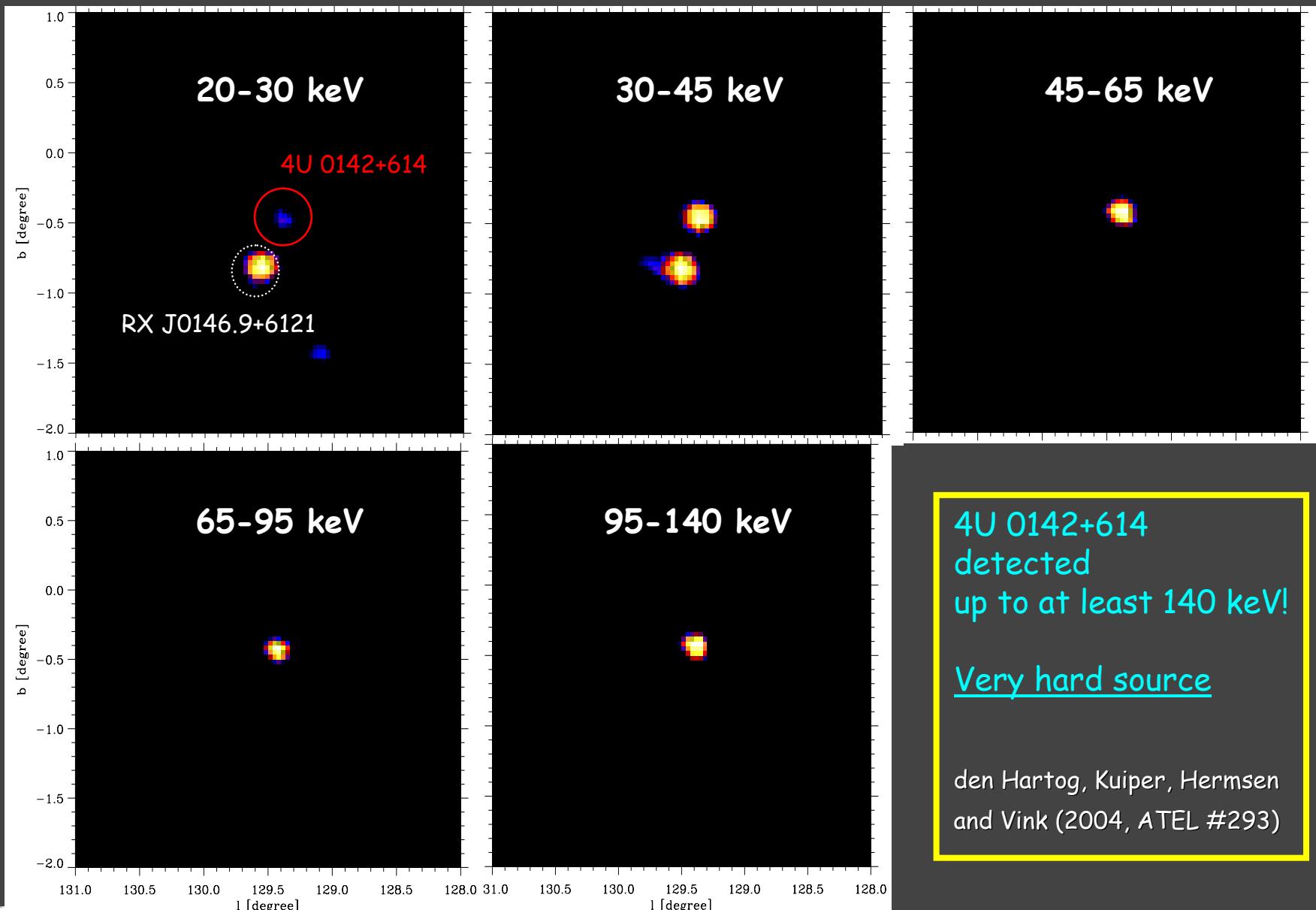
5 Pulsed
1E 1841-045
RXTE/HEXTE

6 Pulsed
1E 1841-045
IBIS ISGRI
 $\Gamma = 0.72 \pm 0.15$

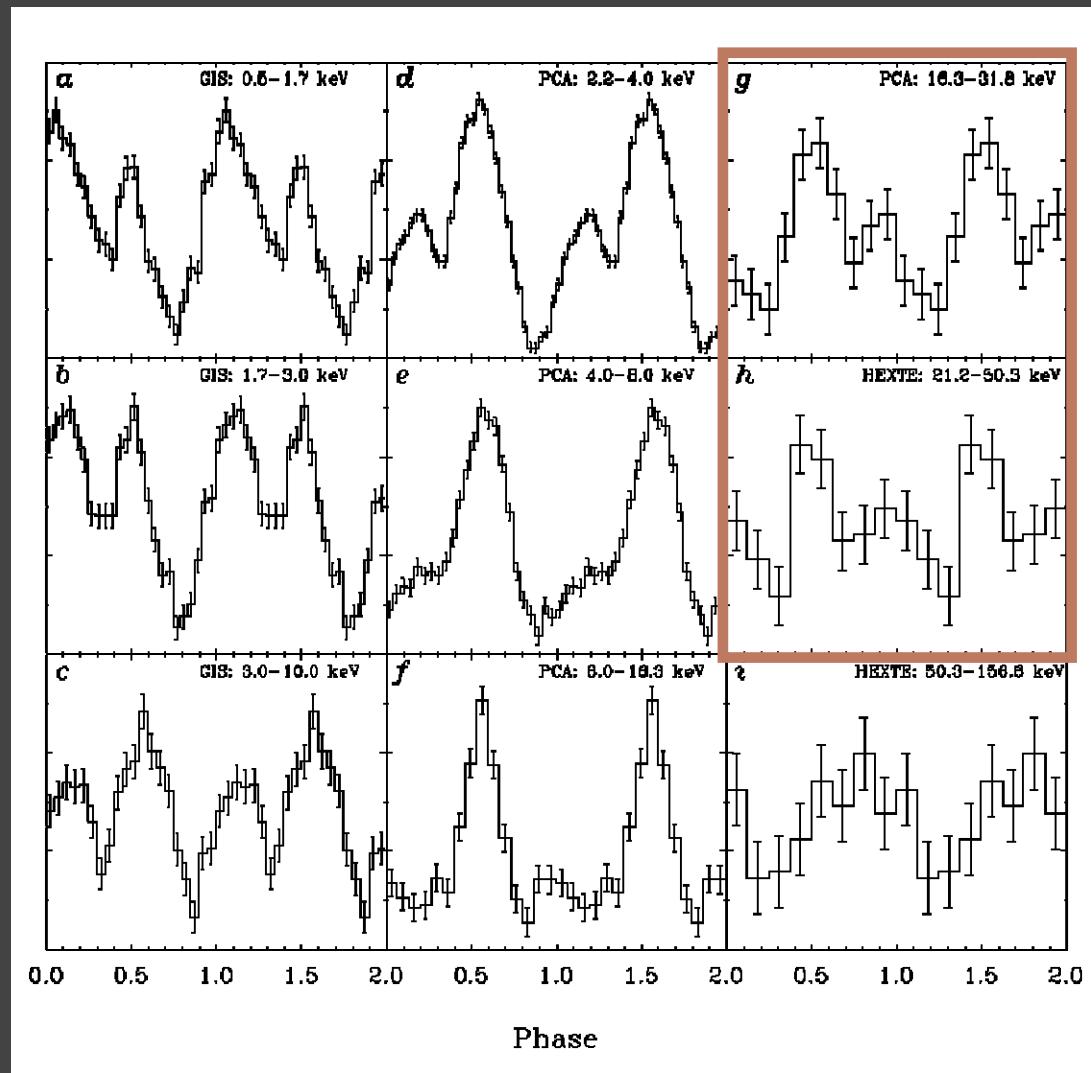
7 Total
1E 1841-045
COMPTEL



AXP 4U0142+614; IBIS ISGRI 2.1 Ms Observation



AXP 4U 0142+614; Profiles ASCA GIS, RXTE PCA/HEXTE



5.7σ

3.4σ

2.1σ

High Energy Spectra of AXP 4U 0142+164

1 Chandra
DC+Pulsed

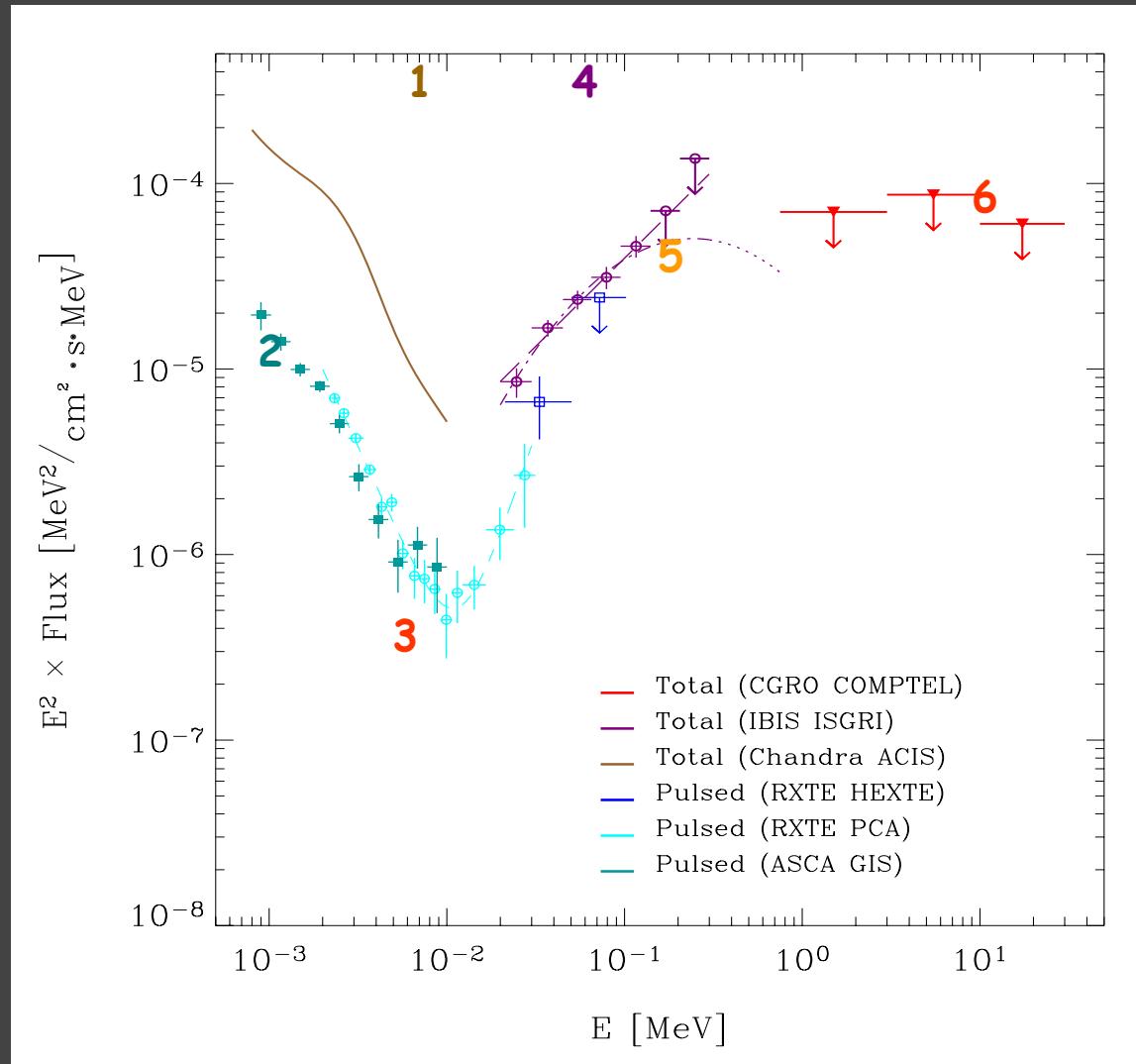
2 ASCA GIS
Pulsed

3 RXTE PCA
Pulsed
 $\Gamma_s = 4.1$
 $\Gamma_h = -0.8$

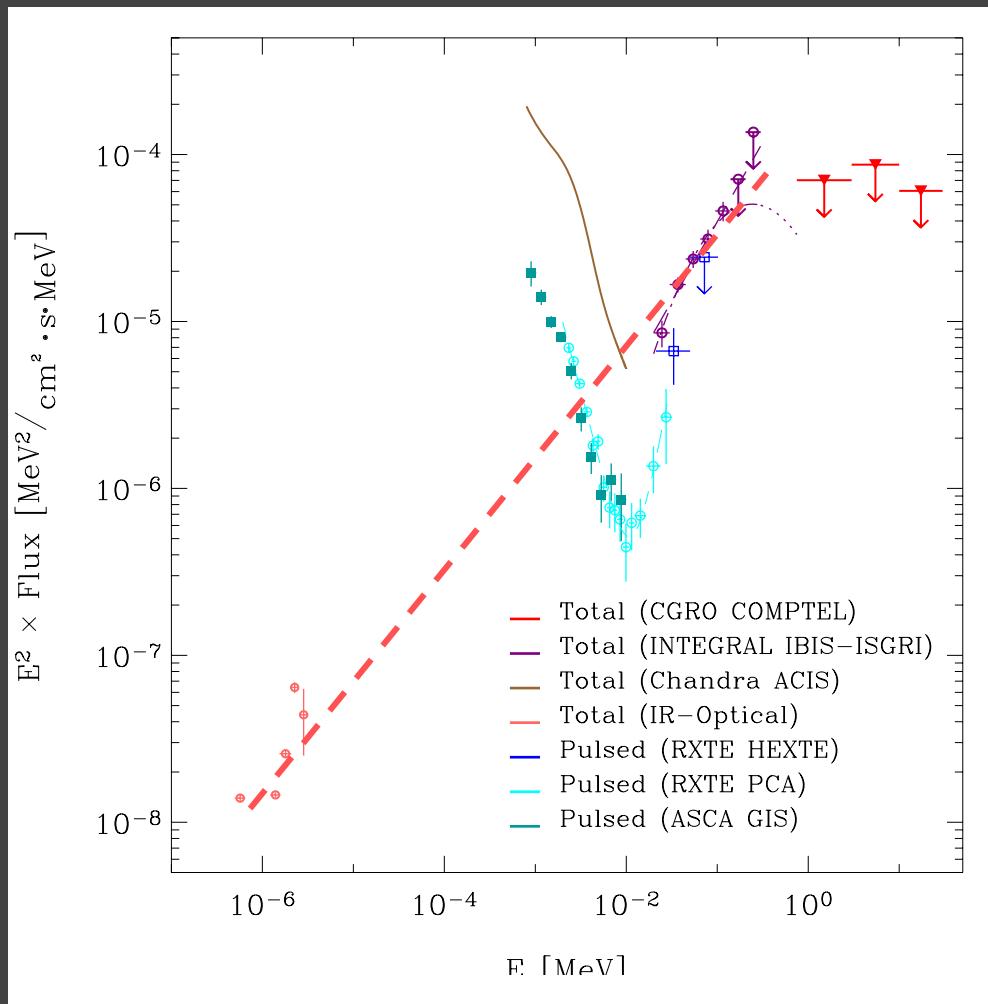
4 IBIS ISGRI
DC+Pulsed
 $\Gamma = 1.05 \pm 0.11$

5 RXTE HEXTE
Pulsed

6 CGRO
COMPTEL
DC+Pulsed



AXP 4U 0142+614



$$L_{\text{spin down}} = 1.21 \cdot 10^{32} \text{ erg s}^{-1}$$

10 - 100 keV:

$$L_{\text{total}} = 6.4 \cdot 10^{34} \text{ erg s}^{-1}$$

$$L_{\text{pulsed}} = 6.9 \cdot 10^{34} \text{ erg s}^{-1}$$

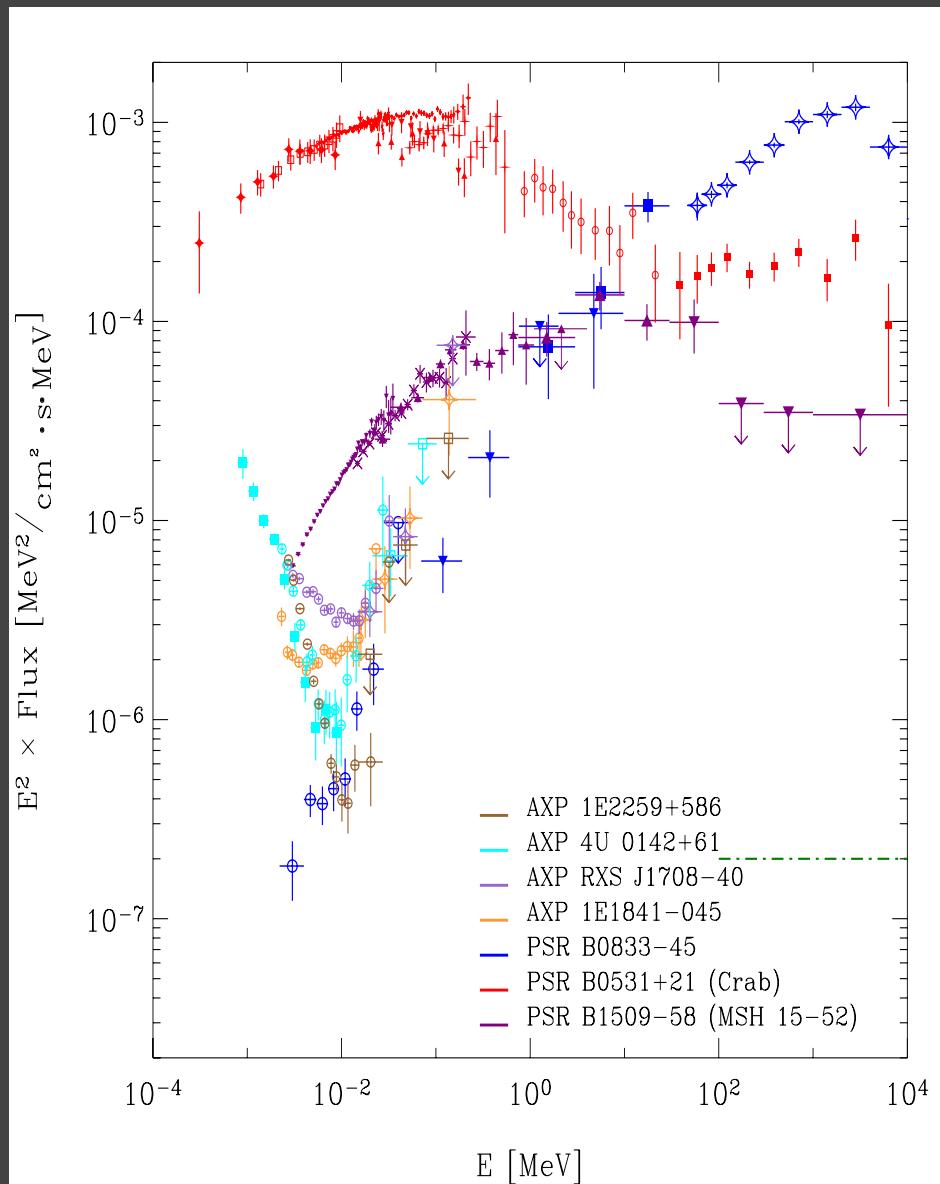
!

Hard X-ray emission linked to IR-Opt?!

Similarities with Vela pulsar; pulsed opt. emission

If underlying mechanism particle acceleration → radio emission

Summary on AXP spectra: Comparison with two young pulsars (Crab and B1509-58) and “middle-aged” Vela pulsar B0833-46



Summary on AXP spectra

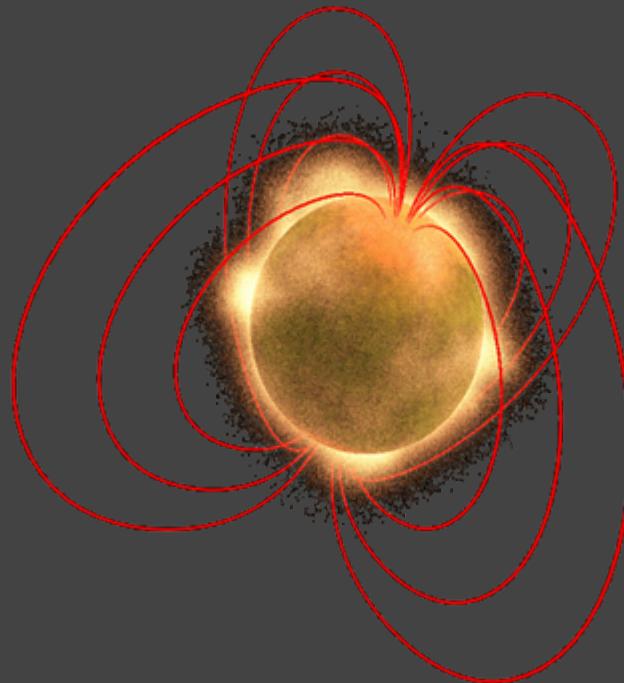
- Hard power-law spectral tails have been detected for at least 3 AXPs: **1E1841-045; 1RXS J1708-4009; 4U0142+614 (1E2259+586)**
- Pulsed emission above 10 keV exceptionally hard with photon indices -1.0 – 1.0
- Pulsed fractions consistent with 100% around 100 keV
- Hard X-ray luminosities (above 10 keV) are \sim 100 to 600 times larger than spin-down power
- Still no indications for spectral bends/breaks till above 100 keV, but these must exist somewhere between 150-750 keV...

Note: Currently 2 radio-pulsars known with $(p, dp/dt)$ in AXP region each with weak X-ray emission: Why do rotating neutron stars with similar P , dP/dt , thus similar B-field manifest themselves so differently?

The Magnetar Model

- A neutron star undergoes vigorous convection during the first ~ 30 s after its formation. When coupled with rotation periods close to the break-up limit ($< 1\text{ms}$), a strong dynamo action will result, which can increase the magnetic field of the core to $\sim 10^{16}$ Gauss.

- Rapid evolution, young systems
- First 10,000 year SGR characteristics
- Next 30,000 year AXPs



(Thompson & Duncan 1992; 1993; 1995; 1996)

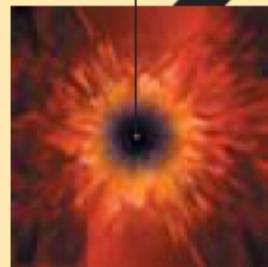
TWO TYPES OF NEUTRON STARS

1 Most neutron stars are thought to begin as massive but otherwise ordinary stars, between eight and 20 times as heavy as the sun.



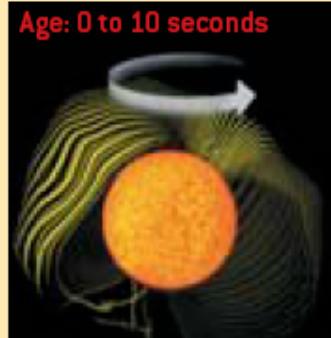
2 Massive stars die in a type II supernova explosion, as the stellar core implodes into a dense ball of subatomic particles.

NEWBORN
NEUTRON
STAR



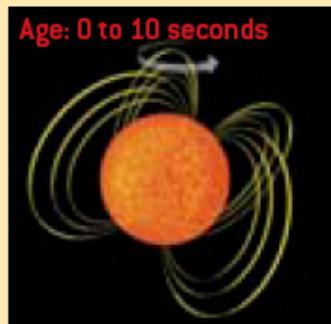
MAGNETAR
↓
ORDINARY PULSTAR

3 A: If the newborn neutron star spins fast enough, it generates an intense magnetic field. Field lines inside the star get twisted.



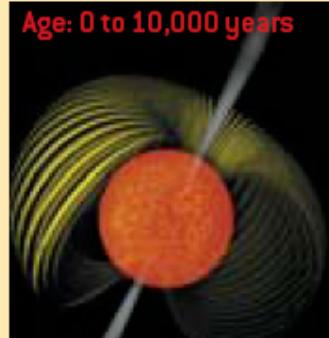
Age: 0 to 10 seconds

3 B: If the newborn neutron star spins slowly, its magnetic field, though strong by everyday standards, does not reach magnetar levels.



Age: 0 to 10 seconds

4 A: The magnetar settles into neat layers, with twisted field lines inside and smooth lines outside. It might emit a narrow radio beam.



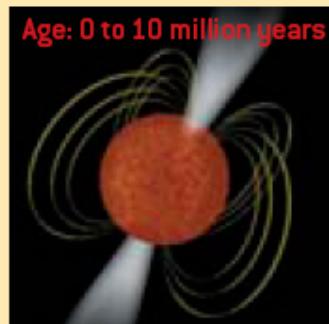
Age: 0 to 10,000 years

5 A: The old magnetar has cooled off, and much of its magnetism has decayed away. It emits very little energy.



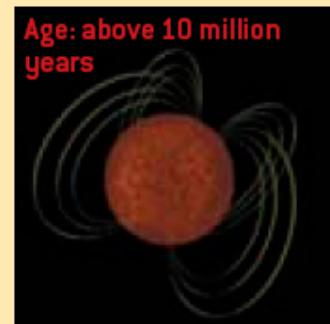
Age: above 10,000 years

4 B: The mature pulsar is cooler than a magnetar of equal age. It emits a broad radio beam, which radio telescopes can readily detect.



Age: 0 to 10 million years

5 B: The old pulsar has cooled off and no longer emits a radio beam.



Age: above 10 million years

Magnetar fields: how are they different compared to radio pulsars?

Thompson & Duncan 2001

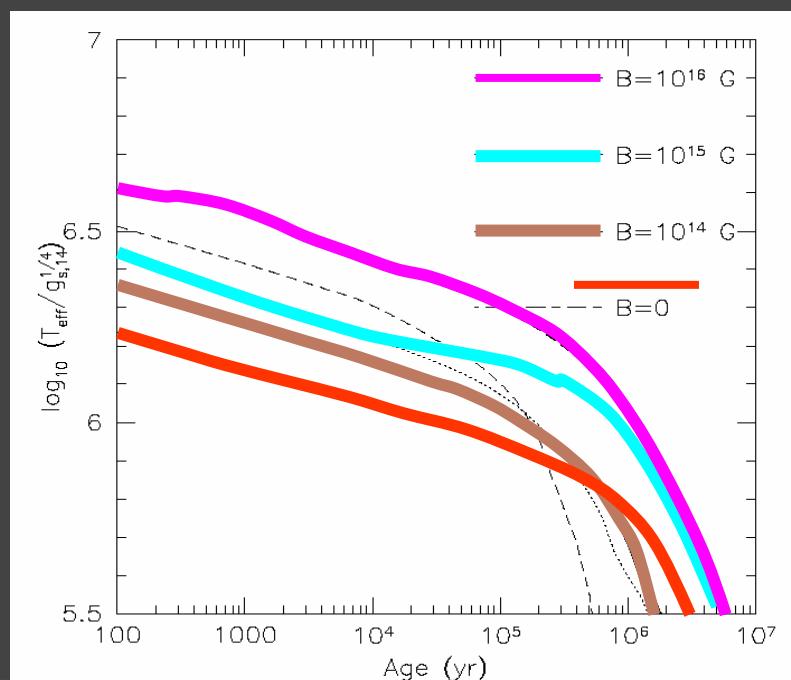
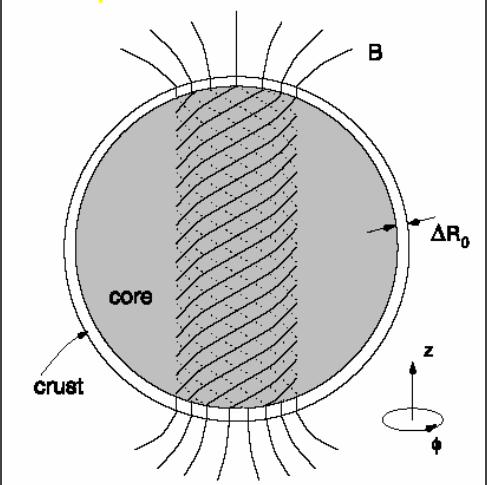
- Faster field decay rate (ambipolar diffusion)

$$t_{amb} \cong 10^5 \text{ yr} \left(\frac{B_{core}}{10^{15} G} \right)^{-2}$$

- Greater crustal stresses

$$B_{yield} = 2 \times 10^{14} G \left(\theta_{\max} / 10^{-3} \right)^{1/2}$$

- Toroidal core field can twist external field when $B_{core} \sim 10^{15} G$
- Greater heat flux through crust



Heyl & Kulkarni 1998

Magnetar burst emission

Thompson & Duncan 1996

- **Giant Flares:**

Diffusion over long time leads to large-scale re-arrangement of the field through:

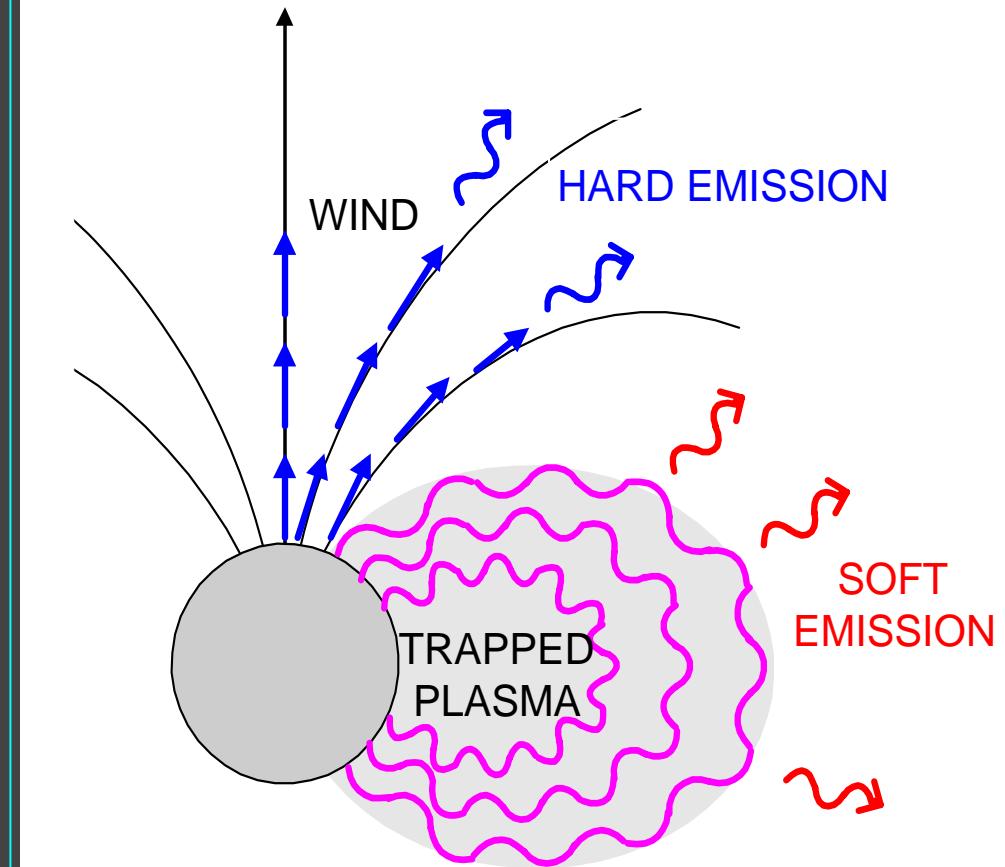
- 1) shear of external field →
reconnection
- 2) interchange instability in fluid core
→ rearrangement of both internal and external field
→ reconnection

$$\frac{B_{core}^2}{8\pi} R^3 \approx 4 \times 10^{46} \text{ erg} \left(\frac{B_{core}}{10^{15} G} \right)^2$$

- **Small Bursts (SGR events):**

Cracking of crust → small displacements of magnetic footpoints
Alfvén waves →

$$E_{SGR} \approx 10^{41} \text{ erg} \left(\frac{B_0}{10^{15} G} \right)^{-2} \left(\frac{l}{1 \text{ km}} \right)^2 \left(\frac{\theta_{max}}{10^{-3}} \right)^2$$



Magnetar thermal quiescent emission

- Powered by decaying B field (Duncan & Thompson 1996)
- Conduction of heat from core
→ heating of crust

Ho & Lai 2004

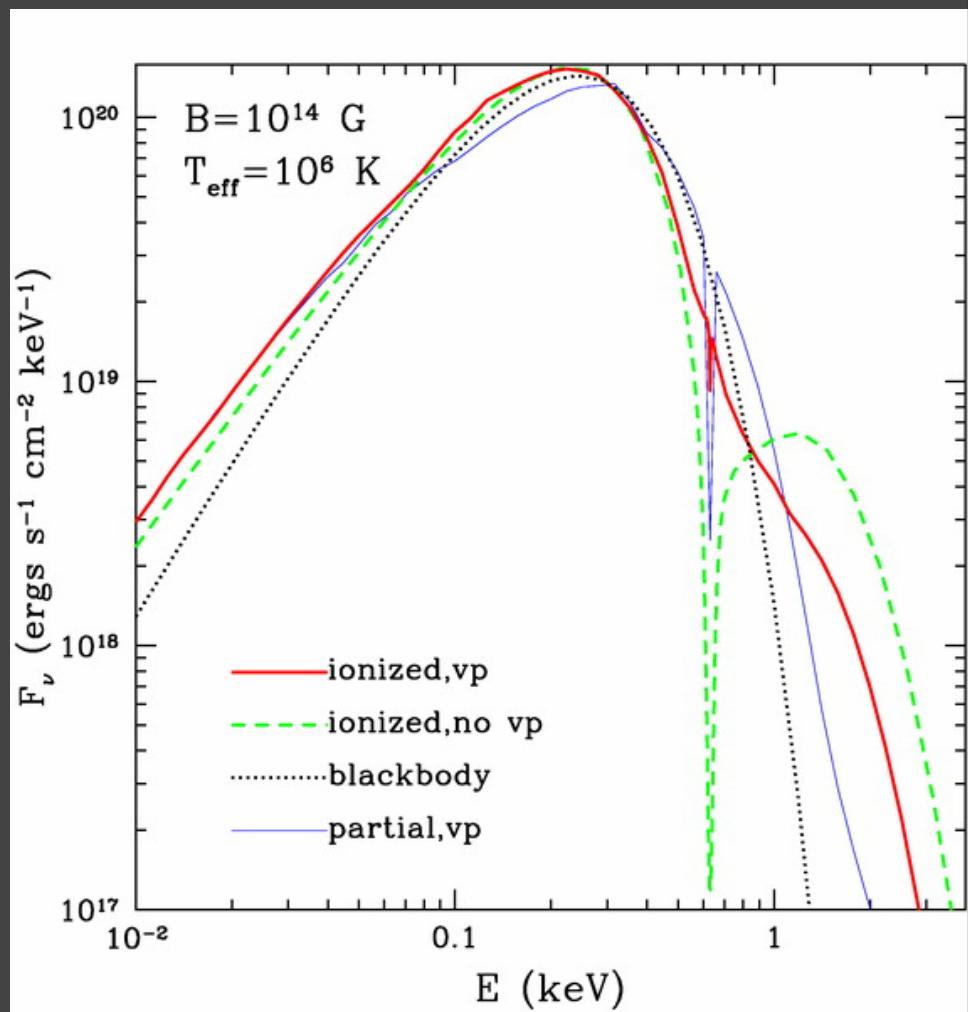
$$T_{\text{crust}} \approx 1.3 \times 10^6 \text{ K} \left(\frac{T_{\text{core}}}{10^8 \text{ K}} \right)^{5/9}$$

$$\Rightarrow L_x \approx 6 \times 10^{35} \text{ erg s}^{-1} \left(\frac{B_{\text{core}}}{10^{16} \text{ G}} \right)^{4.4}$$

Vacuum polarization suppresses cyclotron features!

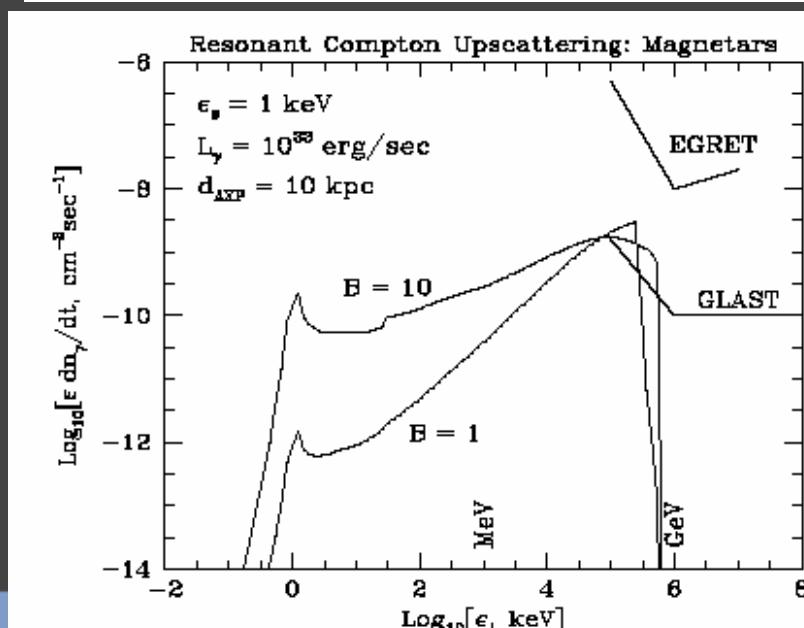
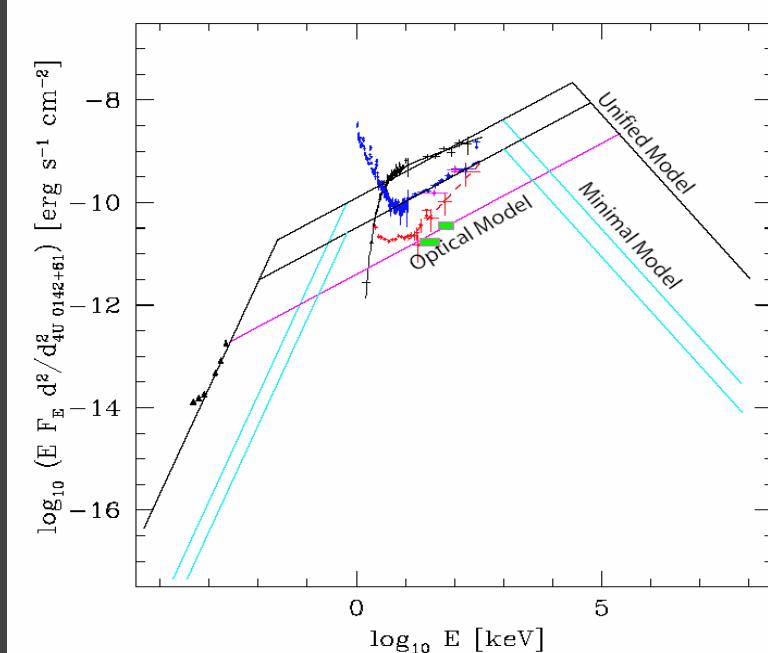
Do magnetars have atmospheres at all?

SRON



Magnetar non-thermal quiescent emission

- Strong $E_{||}$ induced by twisting of field in closed region (Thompson & Beloborodov 2005)*
 - excite Langmuir turbulence in surface layers
 - synchrotron radiation from electron acceleration at high altitude
- Pulsations??
- Shocks from fast-mode plasma waves → pair-synchrotron cascade (Heyl & Hernquist 2005)
- Resonant Compton upscattering of thermal X-rays by accelerated particles in open field region (Baring 2004)
- *) See also Extensive paper on "Corona of Magnetars" by Beloborodov & Thompson 2006



End remark

- Over the last 5 years enormous progress in observational studies, constraining and stimulating further detailed theoretical and observational studies of magnetars!